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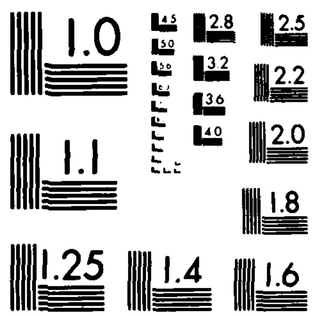

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CAORF 42-8114-02

CAORF TECHNICAL REPORT

SIMULATION EXPERIMENT

TUG USAGE WITH IMPAIRED MANEUVERABILITY

DEPARTMENT OF TRANSPORTATION

MARITIME ADMINISTRATION
OFFICE OF RESEARCH AND DEVELOPMENT

NATIONAL MARITIME RESEARCH CENTER
KINGS POINT, NEW YORK 11024

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16. Abstracts

The investigations described in this report represent a second in a series of investigations planned at CAORF to study the effectiveness of tugs in restricted waterways and the variability in pilot operating procedures. One part of the previous study was concerned with the effectiveness of tugs in assisting an 80,000 DWT and a 250,000 DWT tanker following a complete failure with rudder amidships and a loss of engine power simultaneously, and just before entering a 45° turn. Because such a combined failure is extremely severe and has a low probability of occurring, the present study aimed at more realistic failure conditions on a rudder failure (amidships), or no failure at all could occur at any of the four locations prior to the turn, or four locations in the turn. In addition, the failure could be followed by a recovery in a realistic time period, or no recovery at all. Twelve subjects took part in the experiment; six had tugs available and six had no tugs. They performed a total of 12 runs apiece, and experienced engine and rudder failures with and without recovery and at various locations in an order consistent with the statistical experiment design.

The data from the experiment were examined qualitatively and selected performance measures were subjected to statistical analyses. Based on these practically useful observations, conclusions were drawn from both the non-failure and failure runs regarding pilot procedures with helm, engine and tug power in relationship to the type and location of the failure.

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17b Identifiers/Open-Ended Items

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TUG USAGE WITH IMPAIRED MANEUVERABILITY

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EXECUTIVE SUMMARY

BACKGROUND

Limitations in shiphandling capability can impose significant safety and economic penalties through the need for reduced speeds and the use of tug support. As tanker size has progressively increased the support role of the tug has become more crucial to safety of passage. As a consequence CAORF has embarked on a series of on-line experiments to evaluate more clearly the effectiveness of tugs in harbor operations. These experiments have been designed to investigate the use of tugs for control and deceleration, when maneuverability is impaired, when turning the ship prior to berthing and finally during berthing and unberthing operations.

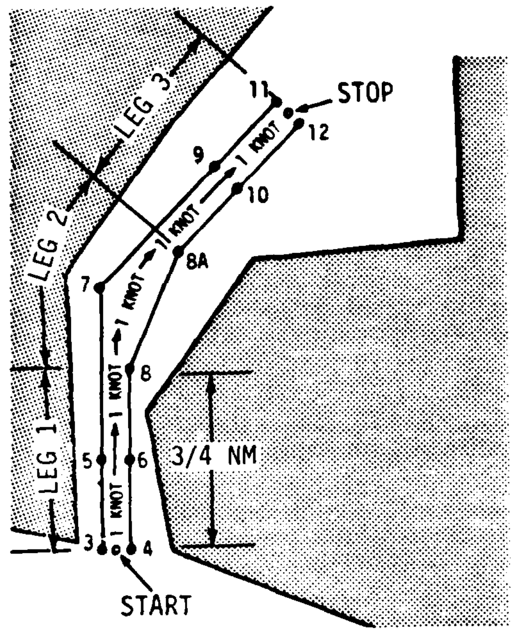


Figure ES-1. Harbor Configuration

The results of the first experiment of the series, "Tug Usage for Control and Deceleration in Restricted Waterways," have been reported in CAORF Technical Report, CAORF 42-8009-02 (December 1982). The scenario used for both that experiment and the present study presented an initial deceleration zone of 3/4 n mile, leg 1, after entering from the ocean. This was then followed by a 45° turn. On emerging from the turn the ship can eventually be slowed down to a low speed midway between two gated buoys 3/4 n mile along the third leg. The channel was 800 feet wide along the two straight legs and was widened in the turn to approximately twice that value. The ships experienced an average wind from northwest of 30 knots, in addition to a 1 knot flood current. The harbor configuration is shown in Figure ES-1.

Twenty-four harbor pilots and 24 docking masters took part in the experiment. The harbor pilots did not have tugs available (except in the case of mechanical failures) whereas the docking masters had tugs available at all times. Two levels of tug horsepower were used (4000 and 8000 HP), each distributed between two and four tugs. Two ships were considered -- a familiar 80,000 DWT tanker and a less familiar 250,000 DWT tanker.

The overall shiphandling techniques were very similar in the two groups. Even though they had tug assistance at all times, the docking masters preferred to rely almost entirely on conventional controls (helm and engine rpm) to negotiate the turn and only used their tugs during the final stopping phase. This is the point where

most difficulty was experienced under normal conditions due to the low speed of the ship, the strong port beam wind, the following current and the loss of rudder control effectiveness when the engines are running in reverse to provide the maximum deceleration.

The tendency was to sail the larger ship at a higher speed in the first leg and in the turn, thereby minimizing the wind effects. In the final leg the larger ship decelerated so that the mean speeds of both ships were comparable in that leg. The use of tugs with the 80,000 DWT ship was negligible, indicating that the pilots were capable of handling this ship size without tugs under normal conditions.

However, due to its higher speed in the turn and its much higher inertia the 250,000 DWT tanker required considerable tug assistance to safely decelerate in the final leg.

In addition to their three normal consecutive runs, all pilots experienced a complete engine and rudder failure (without recovery) just prior to entering the turn on their final (fourth) transit. The rudder was assumed to remain amidships immediately following the failure. All had tugs present in the attendance mode. Tugs were defined to be in attendance when already attached to the ship at positions selected by the pilot and, therefore, available for fairly rapid control. This combined failure presented great difficulty to the majority of the pilots in this scenario, particularly with the larger ship and the lower tug horsepower. Even those pilots who successfully avoided grounding experienced considerable difficulty at various sections of the harbor during transit. There were large variations in the time lapse before pilots applied their tugs, and in this confined waterway such time delays were critical.

In the case of the 80,000 DWT tanker, groundings occurred principally in the final leg where the ship was susceptible to the strong beam wind and the following current. The 250,000 DWT tanker generally grounded in the turn. Because of its greater speed and greater inertia it did not respond sufficiently to the tug forces at either power level. Consequently, in most cases it failed to make the turn.

A simultaneous rudder and engine failure without recovery has a very low probability of occurrence; yet, should it occur, the consequences could be serious in relatively confined waterways as indicated by this previous study. The probability of an engine failure alone or a rudder failure alone, with or without recovery in a finite time is much greater. The investigation described in this present report has considered these failure conditions on a 250,000 DWT tanker with 8000 tug horsepower available.

EXPERIMENT DESCRIPTION

This present study represents the second of a three part investigation into tug usage in harbors. There are three essential phases in these tug operations.

1) Use of tugs for deceleration and control.

2) Tugs in emergency procedures.

3) Use of tugs for turning and berthing.

Tugs are required for this second operation and for safety reasons should be available at all times in restricted waterways in case of an engine/rudder

failure which could inevitably end up in a collision, ramming or a grounding. If tugs are not already attached to the ship (in the attendance mode), but merely escorting the ship (in the assistance mode), the time lapse occurring after an emergency takes place and before they can become effective may be excessive so that a grounding cannot be avoided. Finite times are also required to remedy a rudder failure (at least three minutes) or an engine power failure (at least six minutes), so that again these efforts will be unable to save the ship. The safest technique is to limit the ship speed and provide tugs in the assistance mode at all times. The present experiment has as an objective to investigate the effectiveness of two tugs of 4,000 HP each, assisting a 250,000 DWT tanker in negotiating a hypothetical harbor under realistic environment conditions. The study falls essentially into two phases: Phase 1, where the ship is maneuvered without any tugs being present, whereas in Phase 2, the ship has the two tugs in attendance at all times to reduce speed and effect the turning and final stopping maneuvers as desired. The requirement is made in both cases to be stopped relative to the ground at a point about 3/4 n mile outside the 45° turn, in the presence of a strong wind and a flood current. Twelve subjects were selected from the group of harbor pilots who had participated in the previous experiment (see CAORF 42-8009-02, December 1982) but had not been involved in any runs on the 250,000 DWT tanker.

EXPERIMENT DESIGN

The experiment design used for this study is shown in Tables ES-1, ES-2, and ES-3.

In Group 1 (Table ES-2), six subjects conning a 250,000 DWT ship performed the experiment with no tugs in attendance. The pilots were permitted to use forward and/or reverse rpm for control and deceleration in attempting to stop at the assigned point on the channel centerline between buoys 11 and 12 (Figure ES-1).

The speed of the ship on entering the harbor from the sea outside (midway between buoys 3 and 4, Figure ES-1) was seven knots through the water in all cases.

A second group (Table ES-3), comprising a further 6 subjects on the same 250,000 DWT ship performed the same task but in this case they had two 4,000 HP "Tina" type tugs in attendance at all times. In all cases the wind was gusting at 30 ± 10 knots and the direction varied ± 30° about the 315° point. The current was a following current of 1 knot strength, directed along the channel axis.

The two groups were given a familiarization run without wind and current; this was designed to acquaint them with the ship characteristics, the scenario, navaids, etc.

Each subject then made a total of twelve runs with and without tugs (Group 2 and Group 1 respectively). They were subjected to failures of rudder or engine, but not in combination, either without recovery or with recovery after a finite time. At failure the rudder angle immediately becomes fixed at zero. A five minute recovery period was used for the rudder failure and ten minutes for an engine failure. In some runs they had no failure at all. These failures are more appropriate to actual life operations than the total rudder plus engine failure without recovery used in the previous experiment.

TABLE ES-1. EXPERIMENT DESIGN

Design Structure: 4 Factor Mixed Design
1 between Factor, 3 within Factors

Independent Variables Investigated:

C - Tug Assistance:	C_1 - No Tugs	
	C_2 - Tugs	
E - System Failed:	E_1 - Engine	
	E_2 - Rudder	
T - Time Course of Failure:	T_1 - 0 sec (no failure)	
	T_2 - Average Recovery (5 minutes for the rudder, 10 minutes for the engine)	
	T_3 - ∞ sec (no recovery)	
P - Position in Channel	P_1 - Leg 1*	
	P_2 - Turn (Leg 2)*	

* Failure will occur at any one of 4 positions in either channel segment, see Figure ES-2, which were randomly determined for each subject.

The total number of subjects = 12
Combination of E (E_1, E_2), T (T_1, T_2, T_3) and P (P_1, P_2) factors.

1 - $E_1 T_1 P_1$	$\underline{5}$ - $E_1 T_2 P_1$	$\underline{9}$ - $E_1 T_3 P_1$
2 - $E_1 T_1 P_2$	$\underline{6}$ - $E_1 T_2 P_2$	$\underline{10}$ - $E_1 T_3 P_2$
3 - $E_2 T_1 P_1$	$\underline{7}$ - $E_2 T_2 P_1$	$\underline{11}$ - $E_2 T_3 P_1$
4 - $E_2 T_1 P_2$	$\underline{8}$ - $E_2 T_2 P_2$	$\underline{12}$ - $E_2 T_3 P_2$

_ Designates Failure Run

TABLE ES-2. RUN ORDER - NO TUGS (C_1)

S_1	S_2	S_3
1 - RI - Turn - 2	1 - EI - Leg 1 - 2	1 - None
2 - EI - Leg 1 - 1	2 - RA - Leg 1 - 3	2 - None
3 - None	3 - EI - Turn - 3	3 - RI - Turn - 4
4 - None	4 - None	4 - EI - Leg 1 - 3
5 - EQ - Turn - 3	5 - None	5 - RA - Turn - 3
6 - RA - Turn - 1	6 - RI - Leg 1 - 1	6 - RA - Leg 1 - 2
7 - EI - Turn - 4	7 - None	7 - None
8 - EA - Leg 1 - 2	8 - EA - Turn - 4	8 - None
9 - None	9 - EA - Leg 1 - 4	9 - EI - Turn - 1
10 - RI - Leg 1 -3	10 - RI - Turn - 1	10 - EA - Leg 1 - 1
11 - None	11 - RA - Turn - 2	11 - RI - Leg 1 - 4
12 - RA - Leg 1 - 4	12 - None	12 - EA - Turn - 2
S_4	S_5	S_6
1 - None	1 - EA - Turn - 3	1 - RA - Turn - 2
2 - RA - Turn - 4	2 - None	2 - EA - Leg 1 - 1
3 - None	3 - RA - Turn - 1	3 - None
4 - RI - Turn - 3	4 - EI - Turn - 4	4 - EA - Turn - 4
5 - RA - Leg 1 -1	5 - RI - Leg 1 - 1	5 - EI - Turn - 1
6 - EA - Turn -1	6 - None	6 - None
7 - None	7 - RI - Turn - 2	7 - None
8 - EI - Turn - 2	8 - RA - Leg 1 - 4	8 - EI - Leg 1 - 2
9 - RI - Leg 1 - 2	9 - None	9 - RI - Turn - 3
10 - EI - Leg 1 -4	10 - None	10 - RA - Leg 1 -3
11 - EA - Leg 1 - 3	11 - EI - Leg 1 - 3	11 - None
12 - None	12 - EA - Leg 1 - 2	12 - RI - Leg 1 - 4

I = infinite time for recovery (T_3)
A = average time for recovery (T_2)
None = zero recovery time (no failure, T_1)

E = Engine (E_1)
R = Rudder (E_2)

Leg 1 = P_1
Turn = P_2

The final numeral defines the position of failure in leg 1 or the turn as indicated in Figure ES-1.

TABLE ES-3. RUN ORDER - TUG ASSISTANCE (C_2)

S_7	S_8	S_9
1 - EI - Turn - 2	1 - EA - Leg 1 - 3	1 - None
2 - None	2 - EA - Turn - 2	2 - RI - Leg 1 - 3
3 - None	3 - RA - Leg 1 - 1	3 - EI - Leg 1 - 2
4 - RA - Turn - 3	4 - RI - Leg 1 - 2	4 - RA - Leg 1 - 4
5 - None	5 - None	5 - EA - Leg 1 - 1
6 - EA - Leg 1 - 4	6 - RI - Turn - 1	6 - EI - Turn - 4
7 - RI - Leg 1 - 3	7 - EI - Leg 1 - 4	7 - RA - Turn - 1
8 - RI - Turn - 4	8 - None	8 - None
9 - RA - Leg 1 - 2	9 - None	9 - None
10 - None	10 - None	10 - EA - Turn - 3
11 - EA - Turn - 1	11 - EI - Turn - 3	11 - RI - Turn - 2
12 - EI - Leg 1 - 1	12 - RA - Turn - 4	12 - None
S_{10}	**S_{11}**	**S_{12}**
1 - RI - Leg 1 - 4	1 - None	1 - RA - Leg 1 - 1
2 - None	2 - EI - Turn - 2	2 - RI - Turn - 3
3 - EA - Turn - 1	3 - RI - Leg 1 - 1	3 - EA - Leg 1 - 3
4 - None	4 - EA - Leg 1 - 4	4 - None
5 - RI - Turn - 4	5 - None	5 - EI - Leg 1 - 4
6 - None	6 - EI - Leg 1 - 3	6 - None
7 - EA - Leg 1 - 2	7 - RA - Leg 1 - 2	7 - EA - Turn - 2
8 - RA - Turn - 2	8 - None	8 - RI - Leg 1 - 2
9 - EI - Leg 1 - 1	9 - EA - Turn - 4	9 - RA - Turn - 4
10 - EI - Turn - 3	10 - RA - Turn - 3	10 - None
11 - RA - Leg 1 - 3	11 - None	11 - None
12 - None	12 - RI - Turn - 1	12 - EI - Turn - 1

I = infinite time for recovery (T_3)
A = average time for recovery (T_2)
None = zero recovery time (no failure, T_1)

E = Engine (E_1)
R = Rudder (E_2)

Leg 1 = P_1
Turn = P_2

The final numeral defines the position of failure in leg 1 or the turn as indicated in Figure ES-1.

The failures were also designed to occur at eight specific points along leg 1 and in the turn as shown in Figure ES-2. The failures and their positions along with recovery were automatically controlled within the simulator.

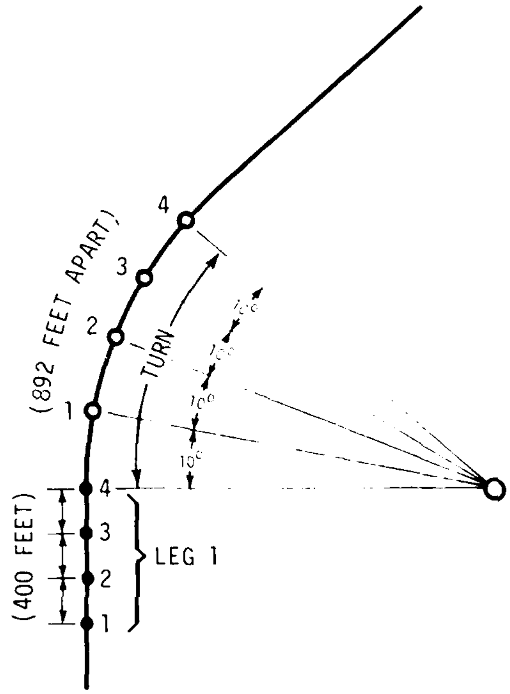


Figure ES-2. Location of Failure Points in Leg 1 and 45° Turn (Leg 2)

HARBOR DESCRIPTION

The simple channel configuration used in this experiment is shown in Figure ES-1. The spacings between buoys along the straight legs are uniformly 3/8 n mile. The channel is 800 feet wide along the straight legs and is widened in the turn to approximately twice this value.

The scenario presents an initial deceleration zone of 3/4 n mile. During this time, the ship can be slowed down progressively if necessary to permit the tugs to pass towing hawsers and safely lash up alongside the ship. In order to simulate real-world conditions, a five-minute time delay was imposed after entering the channel before the tugs could become effective. This is then followed by a 45° turn (which represents both the recommended maximum heading change acceptable in a harbor waterway, and also a smooth transition curve radius of at least five times the length of the largest ship using the channel). On emerging from the turn, the ship can eventually slow down to stop midway between the gated buoys 11 and 12, 3/4 n mile (or approximately four or five ship lengths) along this third leg.

CHANNEL DIMENSIONS

The water depths inside the channel and outside have been chosen so that the depth/draft ratio is 1.15, so as to give realistic harbor shallow water effects. The depth of water outside the channel section is adequate for safe operation of the selected tugs.

ENVIRONMENTAL CONDITIONS

Wind. The wind in the harbor was assumed to be gusting with a strength of 30 ± 10 knots from the NW approximately (315° ± 30°).

Current. A flood current was assumed to flow in the channel direction at 1 knot speed. In the 45° turn it flows along the transition arc of radius 5,100 feet, which is tangential to the centerline of leg 1 and leg 2 at the buoy locations 8 and 8A respectively.

OWNSHIP AND TUG CHARACTERISTICS

A large 250,000 DWT tanker was used as Ownship in these experiments (Table ES-4). It represents a ship of very large tonnage familiar to only a few pilots in U.S. waters.

TABLE ES-4. OWNSHIP CHARACTERISTICS

	250K Tanker
Length (L)	1,085 ft.
Draft (T)	65 ft.
Beam	170 ft.
Depth/Draft	1.15
Ahead HP	36,000
Prop. Dia.	29.2 ft.
Max. Rudder Angle	35°
Rudder Area (A_R)	1,302 ft.^{2}
Rudder Area Ratio (A_R/LT)	0.018

The following simulations were available for the ship and were used during these experiments:

1) Zero/low speed hydrodynamics.

2) Aerodynamics.

3) Shallow water effects.

4) Bank effects.

However, squat and modified trim in restricted shallow waters and wave forces (all of which would be small in this scenario) were not included in the simulation.

Tug Simulation

For the present experiments the "simple" tug simulation option on the advanced tug simulator was employed. This permitted specific information on the forces and moments exerted by each tug to be recorded directly on the summary datalogs. Fortunately the assumptions implied in using this simplified form (constant thrust and angle of application independent of ship speed, tug capabilities, etc.) could be used with some confidence based upon the results of the sea-trials involving the "Tina" (a 1,000 HP tug with 360° steerable propulsion units and Kort nozzles) and the 25,000 DWT USNS "Yukon." An examination of the data from these trials indicated that if a maximum bollard pull of a constant 27,000 pounds were adopted independent of ship speed (but less than 6 knots), hawser angle and propulsion unit angle, the maximum error would never exceed 10%. Such an assumption was ideal for our purposes, and consequently tugs with "Tina's" characteristics were built into the present experiment. The characteristics of the "Tina" tug are tabulated in Table ES-5.

The 4000 BHP tugs assumed in th... study were considered to be simply a scaled version of the basic tug. These tugs can contribute maximum thrusts of the order of 27,000 pounds on a continuous basis at any heading and, hence, without the tug having to be repositioned control of Ownship can be maintained at all times. Full thrust can be obtained aft and broadside as well as forward, which permits a minimum amount of line handling while docking.

Tug Display

During the simulation exercise, the pilot was at a disadvantage in that he could not check tug locations by peering out of the wheelhouse. To compensate for this deficiency the pilot was presented with a display of the ship's planform and the relative tug positions using a closed-circuit TV monitor.

TABLE ES-5. CHARACTERISTICS - WILMINGTON LAUNCH TUG TINA

Length Overall	65.0 ft.
Beam, Molded	26.0 ft.
Draft, Molded	9.0 ft.
Draft to Bottom of Skeg	10.5 ft.
Displacement (Design)	127.5 tons
Brake Horsepower	1,000 HP

Propulsion. Two diesel engines coupled to Murray and Tregurtha 360-degree steerable propulsion units with propellers in Kort nozzles. The two propellers are mounted aft. The tugboat is designed to operate as a tractor tugboat when going astern.

Propellers. Right-hand, four-bladed, Kaplan type; 5.33 feet diameter in a Kort nozzle.

EXPERIMENT PROCEDURE

TEST SUBJECTS

The twelve pilots who participated in this experiment were drawn from the harbor pilots who took part in the previous experiment on Tug Usage for Control and Deceleration (McIlroy, 1982), but had not been involved in the runs with the 250,000 DWT tanker.

They comprised six pilots from New York and six pilots from Delaware. They were very familiar with the harbor and environmental effects (on the smaller ship) but not accustomed to this larger ship.

Preliminary Operations

Before performing his experimental runs, the pilot was briefly introduced to the CAORF bridge and its equipment, the properties of the visual scene and the specific procedures that would be used.

The pilot was then briefed by a member of the CAORF staff who discussed the scenarios, channel dimensions, banks, shallow water, winds and currents, ship and tug characteristics, (where appropriate), operating procedures and requirements. He was then provided with a chart of the harbor and a detailed printed booklet duplicating the details of the verbal briefing. The pilot could therefore refer to this document and chart at any time during the experiment should he have any questions. He was told he would perform thirteen runs in all, the first for familiarization and then twelve subsequent runs. He was not told at any time when and where to expect mechanical failures.

The first of his experimental runs was designed to familiarize the pilot with the harbor scenario, the navaids and the ship which he would use throughout his series of runs. During this familiarization run, performed in the absence of external environmental influences, the objectives were identical

to the subsequent runs, namely, to be stopped relative to ground at the end of leg 3.

At the end of each run a short informal briefing was held with each subject by a member of the CAORF Research staff. Questions regarding the subjective reactions to the run, vessel handling, wind and bank effects, tug handling qualities, etc., were explored.

At the end of the series of twelve runs a final debriefing session was held to obtain an overall assessment of the experiment from the pilot and indications of where in his judgement certain aspects may have lacked realism.

DATA COLLECTION

A variety of sources were used for data collection during the running and analyses of the experiment. The major performance measures were obtained or derived from computer summary datalogs, ship's bridge data sheets, and debriefings. The primary source for all objective data during the actual experiment runs was the "playback tape." This is a magnetic recording of important computer and ship state parameters (numbering well over 1,000 items) for each run, taken at a fixed time interval. The recording rate for the experiment was once every 10 seconds.

COMPUTER SUMMARY DATALOGS

Computer summary datalogs are printouts from the playback tapes. This information was made available as hard copy printouts at the end of groups of runs. A total of 64 items were obtained on the printouts and used in the subsequent analyses.

DATA PRESENTATIONS

Data collected during the experiment are presented in the following format for visual interpretation and qualitative evaluation that will complement the conclusions of the statistical analyses of the same data.

- o Ship track plots, derived from the ship's dimensions, the coordinates of the its center of gravity (X_o, Y_o) and its heading as recorded in the data summary at two minute intervals.

This was done for 156 runs, and is presented in two groupings:

1) Twelve familiarization runs.

2) Twelve subsequent runs per subject involving no failures, rudder, and engine failures as indicated in Tables ES-2 and ES-3. The type and location of the failure are indicated on each figure.

- o Simultaneous plots of rudder angle, rudder moment and engine speed variation with time over the duration of runs, for both the active and no tug modes. These data are obtained directly from the data summary. For the active mode these quantities are shown along with the corresponding plots of tug forces and tug moment.
- o Simultaneous plots of tug forces and tug moments are presented for the active tug group, 72 plots in all. The data for these plots were obtained directly from the information in the summary datalogs. In the previous experiment the same data had to be derived from the combined nonhydrodynamic forces and moments and the individual values for wind and banks.

- Plots indicating the mean distance off the assigned track (the centerline in legs 1 and 3, and the transition arc in leg 2) at 400 foot intervals. The individual values of distance off-track were calculated from the ship coordinates at the interpolated time corresponding to each 400 foot increment using the information in the data summary. The data corresponding to the subjects in each combination of factors considered, for example, type of failure (engine, rudder), time course of failure (no failure, average recovery time, no recovery), failure position (leg 1, turn), and tug mode (no tugs, active tugs), were then averaged to obtain the mean distance off-track at that location. At the same time the standard deviation and the extremes of these individual measurements were estimated. The mean, standard deviation and the extremes are all depicted on the plots.

PERFORMANCE MEASURES

A new set of performance measures was introduced in the previous report on Tug Usage for Control and Deceleration in Restricted Waterways, CAORF 42-8009-02. For a full discussion of these measures the reader should refer to the main text of this report (Section 2.11). These measures comprise mean swept path, mean lateral and longitudinal tug forces, and the following, individually and in combination: root mean square (RMS) deviation off-track, RMS rudder angle, RMS tug moment, and the new "inherent risk" factor.

DATA ANALYSIS

The data collected during this study were examined in two ways: qualitatively by visual examination of simultaneous plots of ship tracks and the corresponding control activity, and quantitatively by statistical methods.

QUALITATIVE ANALYSES

The qualitative evaluation was made by examining, comparing, and correlating the various forms of graphical data derived from the experiment. These were studied separately for the non-failure and the failure conditions.

Observations on Non-Failure Runs

Each pilot had four non-failure runs (in addition to his initial familiarization run) in his program interspersed among the failure runs in a random manner, as shown in Tables ES-2 and ES-3. Consequently there resulted twenty-four runs by pilots who did not have any tug assistance and twenty-four more runs where tugs were available and could be used as desired. As stated previously the test subjects in this experiment were harbor pilots who had participated in the previous study but only on an 80,000 DWT tanker and without tug assistance until they experienced the complete mechanical failure. The data were studied by observing ship ground tracks, rudder and rpm variations and tug forces and moments (where appropriate) and comparing the techniques of the pilots.

Observations on Failure Runs

Failures occurred at selected points in the first leg and in the turn as shown in Figure ES-2 and according to the run order schedule of Tables ES-2 and ES-3. They were either due to an engine failure or a rudder failure with rudderangle of zero degrees, but not both simultaneously as in the previous

experiment. These failure modes were further subdivided to allow for either no recovery or for recovery after an expected average time (five minutes for a rudder failure and ten minutes for an engine failure). On re-examining the rudder and rpm time variation corresponding to the non-failure runs discussed previously, it is apparent that rudder was generally amidship for a relatively large percentage of the time in the turn and in leg 1 and also the rpm were generally reduced to slow ahead or dead slow. Under these conditions it would seem that failures occurring in certain locations in either leg but with recovery would not present a problem. Failures without recovery however could present a serious problem, more so in the event of a rudder failure than for engine failure.

Even with a finite recovery time, the location of the rudder failure can be critical. If it should occur in leg 1 just at the point when the turn should be been initiated, then control of the ship through the turn could be difficult without tug assistance. However, if the failure occurred after the turn has been initiated and the ship has developed sufficient turn rate, the loss of rudder for a five minute period may not be serious. Should the rudder failure occur towards the end of the turn when corrective rudder is required, then again problems may be experienced in transiting the final leg without tug assistance.

A loss of engine power on the other hand will not impose such serious consequences. In legs 1 and in the turn where failure occurred the ship has moderate hull speeds (about 5 knots) at which the rudder can be used very effectively despite the loss of the propeller wash on the rudder following failure. Hence sufficient control can be exercised by the rudder, although the ship will slow down more rapidly due to loss of thrust.

The loss of engine power becomes more serious as the ship speed decreases, and at very low speeds it is the propeller wash over the rudder that provides the major contribution to the forces and moments.

The data for the failure runs were examined in relation to the type of failure, the location of the ship at time of failure, the ship's track line prior to and after failure, and the pilot's technique and the occurrence of groundings.

STATISTICAL ANALYSES

The statistical analyses were based on Analysis of Variance procedures (Anova) on the experimental data, supplemented by Neuman-Keuls multiple comparison procedures. An Anova Source Table was generated that gives the significant dependencies of the selected performance measures (17 in number) on the various factors (main effects) and their interactions to significance levels of 0.001, 0.01, and 0.05.

In order to understand quantitatively the importance of the various factors more fully, it was necessary to examine in detail the higher order significant interactions. This was done and the final results are described for a selected number of the performance measures considered - mean speed, swept path, distance-off-track contribution, rudder contribution, tug moment contribution, inherent risk factor, the combined performance measure, and lateral and longitudinal tug forces.

Not all the performance measures treated in the analyses are discussed in detail in the text.

CONCLUSIONS

As a result of the qualitative and quantitative analyses described in this report the following observations and significant conclusions were made:

Non-Failure Cases

- In the absence of mechanical equipment failures pilots generally had little difficulty in completing a successful passage with the 250,000 DWT tanker, a conclusion also reached in the previous investigation. It is only in the final deceleration phase that tug assistance may be desireable, to counteract drift and moment due to the beam wind and following current. Tugs are not generally used in the first leg or in the turn. In the final leg tug use was slight, and occurred with different variations in the degree of use for deceleration, control and yaw moment, or combinations of both. In seven of the twenty-four runs tugs were not used at all.

- The mean track with and without tugs lies to the left of the designated trackline (leg centerlines and transition arc) at all times. In entering leg 3 the mean track is about midway across the left hand side of the channel. This differs from the findings of the previous experiment where the average track lay to the right of channel centerline on entering the turn, crossed over the transition arc about midway in the turn, and entered the third leg about 100 feet to the left of centerline. Hence in this case the mean centerline appears to have been moved bodily about 100 feet to the left. The mean speed of the ship was approximately 0.43 knots higher in the first leg and in the turn than in prior experiments. This higher speed increases the rudder effectiveness and reduces the influence of the wind. There is a decrease in the use of right rudder but an increase in left corrective rudder used, particularly in the final phases. This group of pilots may also have preferred to stay to windward in anticipation of possible mechanical failures occurring.

- With no tugs the standard deviation (consistency) in the turn and the extremes are larger than those when tugs were available, despite the fact that these tugs *were not used.* It was found, however, that the pilots with tugs used slightly higher mean speeds in leg 1 and the turn, and this perhaps led to the more consistent performance.

- As in the previous experiment, some pilots appeared to use an approximately constant heading technique to cut across the turn parallel to the inner edge, whereas others used an approximately constant turn rate and followed the transition arc quite closely.

- The percentage time that right rudder is used was much higher in all legs in the prior experiment than in this experiment. The smaller rudder use may be attributed to the higher mean speeds of the ships in this exper-

iment. In addition, a further factor may be the influence of the bank moments on the ship. In this experiment the mean track of the ships lies to the left of track, especially in the third leg and consequently the ship experiences suction forces and clockwise moments from the interaction with the left bank. These moments are counteracted by the application of left rudder. The bank interaction moment opposes the wind moment and consequently reduces the need for corrections using right rudder. Hence the amount of right rudder should be expected to decrease, whereas the amount of left rudder should increase. The largest difference is indeed found to occur in the final leg.

- During the final deceleration phase in leg 3 the engine rpm's are run at full power astern (~40 rpm). In this case, where the ship speed is still forward ($u > 0$) but engine running astern ($n < 0$), the reverse thrust is close to the maximum that can be exerted by the two 4000 BHP tugs pulling backwards at the stern of the ship (namely 216,000 lb). Consequently the two tugs can compensate adequately for engine power loss in the deceleration mode.

- In the final leg when engines are reversed to provide maximum deceleration and the ship is in forward motion, there is a drastic change in the rudder efficiency and rudder moments. Although the use of full power in reverse leads to a large deceleration force it does not contribute to the rudder effectiveness. For a mean ship speed of 4.5 fps (about 2.7 knots) in this final leg, the rudder moment, using maximum right rudder, equals 8.5×10^6 lb. ft. This is only about one tenth of what could be obtained using the available tug power.

- The swept path in the turn is generally much larger than that in the first leg but decreases in the third leg. When there is no recovery the swept paths in legs 2 and 3 are not significantly different whether tugs are available or not.

Failure Cases

- The highest value of inherent risk occurs in the turn, the next highest in the first leg and the lowest value in the final leg. This is obviously due to the restricted maneuvering area available in this scenario.

- From the rudder and rpm time variations corresponding to non-failure runs it is apparent that the rudder was generally amidship for a relatively large percentage of the time in the turn and in leg 1 and also the rpm's were generally reduced to slow ahead or dead slow. Under these conditions failures occurring in certain locations in either leg but with recovery would not present a problem. Failures without recovery however present a serious problem, more so in the event of a rudder failure than for engine failure.

- With a finite recovery time, the location of the rudder failure can be critical. If it occurs in leg 1 just at the point when the turn should have been initiated, then control of the ship through

the turn is difficult without tug assistance. On the other hand if failure occurred after the turn has been initiated and the ship has developed sufficient turn rate, the loss of rudder for a five-minute period may not be serious. Should the rudder failure occur towards the end of the turn when corrective rudder is required, then again problems may be experienced in transiting the final leg without tug assistance.

- A loss of engine power will not impose such serious consequences. In leg 1 and in the turn where failure occurred the ship has moderate hull speeds (about five knots) at which the rudder can be used very effectively despite the loss of the propeller wash on the rudder following failure. Hence sufficient control can be exercised by the rudder, although the ship will slow down more rapidly due to loss of thrust.

- Calculations of rudder moment at the typical ship and engine speeds at location of failures were made. In the case of a rudder failure and consequently a complete loss of rudder moment, the available tugs could compensate for this loss only if the original rudder angle were less than 20^{o}.

- Similarly in the event of an engine failure it was also shown that due to the reduced propeller wash over the rudder, there was a 30% loss in effective rudder moment. The maximum tug moment available can adequately compensate for this loss if necessary. The loss of engine power becomes more serious as the ship speed decreases, and at very low speeds it is the propeller wash over the rudder that provides the major contribution to the forces and moments.

- The occurrence of a rudder failure at specific locations in the channel and/or without recovery can create a serious situation if tugs are not available to compensate for the loss of turning moment on the ship. The cases of rudder failure without recovery either in the first leg or in the turn caused the pilots to take unique measures to abort their mission when they did not have tug support. In all other cases of failures with or without tugs they continued the transit to the end.

- The following general procedure was adopted by all pilots in the event of a rudder failure without tug assistance. Whether the failure occurs in the first leg or in the turn, the procedure is to immediately brake by putting the engine in full reverse and keeping it there until the failure is corrected or the ship has stopped. The corresponding procedure when tug support is available and failure occurs prior to the turn, is

  1) To decelerate immediately by putting the engine in full reverse,

  2) At the same time use the tugs to provide the necessary yaw moment to initiate the turn (and further deceleration if desired), and then essentially to duplicate the rudder con-

trol processes that have been lost and,

3) Use the tugs for the final deceleration, where it has been found that tug assistance is advantageous at all times for the 250,000 DWT tanker.

If the turn has already been initiated when the failure occurs there is no attempt to decelerate further by using the engine, which is not touched. Tugs are used to compensate for the loss of rudder by providing correcting yaw moments and lateral forces to balance the wind drift and prevent luffing.

o A loss of engine power does not significantly reduce the rudder efficiency at the ship speeds encountered in the first leg or in the turn. The amount of thrust that is lost is also not a significant quantity and can be very easily compensated for by using tugs if available. If tugs are not available then the ship will slow down more quickly. Consequently the rudder effectiveness will be reduced and larger rudder angles will be required for control.

o The following general procedures were adopted by pilots in the event of an engine failure:

Effective control is carried out conventionally using the rudder. When tugs are present they are used primarily for deceleration, although they can also supplement the rudder moments. In the final stages they are effectively used for both deceleration and control.

In this final deceleration phase the ship is totally dependent on the availability of the tugs. This function was carried out primarily by the engine under normal no-failure and rudder failure conditions.

o The contribution of off-track deviation to the combined performance measure is greatest in the turn, next largest in the final leg, and quite low in the first leg in the no-failure condition. There is a significant increase in the third leg for failure conditions when the recovery time is increased.

o The rudder contribution is significantly increased when an engine failure occurs. When the failure takes place in the first leg, significantly more rudder is used to compensate than when failure occurs later. In the turn the difference due to position of failure is not significant. However in the final leg where deceleration is usually performed using the engine, more rudder and tug power are used for deceleration and control; more so when the failure occurs later in the turn.

o In the event of an engine failure in the absence of tug support, values of rudder contribution significantly higher than under the non-failure condition occur in leg 2, and increase with failure time. In leg 3 the difference in rudder contribution between no failure and average failure conditions is insignificant, but changes significantly when there is no recovery. With tug support, however, the only significant difference with failure time

occurs in the third leg. The rudder contribution increases significantly for the average failure time and no further significant increase with extended failure time.

- With rudder failure and no tug support there is a significant effect of failure time in leg 2 on the rudder contribution. Although there is a non-significant change in leg 3 between no failure and average failure, both are significantly different from the case of no recovery. This is due to the fact that the rudder is completely lost in this leg. The same is true when tugs are present.

  The presence of tugs results in the decreased use of rudder in leg 2 for all time-of-failure conditions, and also in the final leg only for the no-recovery condition. For the rudder case, there is significantly more contribution in the turn when tugs are not present and there is no failure, and also in the third leg when recovery takes place.

- The mean longitudinal tug force $\bar{X}_T$ responsible for producing deceleration increases significantly throughout the transit, whether failures take place in the initial leg or in the turn. This retarding force is largest in leg 1 when failure occurs in leg 1, and largest in leg 3 when failure occurs in the turn. In the turn itself the force is essentially independent of the failure location.

- There is a significant increase in $\bar{X}_T$ in the case of an engine failure, especially in the final leg. The value of $\bar{X}_T$ in the third leg increases rapidly as the failure time increases. However, there is no significant difference between the values in the first leg and in the turn.

- In the case of a rudder failure with engine power still available for deceleration, the tugs are used mainly to compensate for the loss of rudder moment rather than deceleration over the major part of the transit.

  As a consequence, the value of the decelerating force does not change significantly in the final (deceleration) leg with the time duration of the failure as it does in the case of an engine failure.

- There is a significantly larger $\bar{Y}_T$ (the lateral tug force that contributes to the turning moment of the ship and to counteracting drift) for the case of rudder failures than for engine failures. This can be related to the fact that when an engine failure occurs tugs are used principally to produce deceleration, and when a rudder failure occurs to produce moments.

  The force is significantly larger as the failure time is increased, but shows no differences due to the actual position of failure. Its value increases with leg, having a maximum value in the terminal leg.

- When failure occurs in the first leg there are significant differences in tug moment contribution between legs 1 and 2 and between 2 and 3. The highest value (.515) occurs in the turn and the values in the first leg

and third leg are not statistically significantly different. This clearly demonstrates the effective use of the tugs for control in the turn ($N_{RMS} \approx 0.72$ times maximum possible tug moment), and less in the third leg where they are principally used for deceleration rather than control.

- The position of failure does not have any effect on the inherent risk for engine failures with and without tug assistance, or rudder failures without tugs, independent of the length of time the failure lasts. However the position of failure is important when a rudder failure occurs and tugs are present -- the risk is greater when failure occurs in the turn. There is a significant decrease in risk as the failure time is increased, due to the presence of tugs for control.

- The risk is larger for an engine failure than with a rudder failure when the failure occurs in the first leg and tugs are in assistance. There is also a significant increase in risk in the turn when the rudder failure occurs in the turn.

- Higher values of the combined performance measure, J2, are produced by engine failures than by rudder failures. The major contributors to this difference are larger off-track deviation and rudder contributions in the case of engine failures. The inherent risks are essentially identical for the two systems. The highest value always occurs in the turn principally due to distance off-track and rudder contributions.

- There is no difference in J2 in any leg due to failure position for an engine failure and with tug support. For a rudder failure, on the other hand, and with tugs available the value of J2 is larger in the turn when failure occurs in leg 1 than when it occurs in the turn.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The U.S. Coast Guard and I.M.C.O. have given top priority to studies of inherent maneuverability of existing and future ships both under normal maneuvering conditions and when maneuverability is impaired due to engine and/or rudder failure. Limitations in shiphandling capability can impose significant safety and economic penalties through the need for reduced speeds and the use of tug support. Ship size may limit the use of an existing harbor and substantial modifications of the harbor would be necessary to accommodate such ships. The environmental conditions for safe operation in the harbor may also be limited by the degree of ship maneuverability so that a given ship may not be permitted to enter the harbor except with the assistance of tugs. Therefore, as tanker size has progressively increased the support role of the tug has become more crucial to safety of passage. As a consequence CAORF has embarked on a series of on-line experiments to evaluate more clearly the effectiveness of tugs in harbor operations. These experiments have been designed to investigate the use of tugs for control and deceleration, when maneuverability is impaired, when turning the ship prior to berthing and finally during berthing and unberthing.

The results of the first experiment of the series, "Tug Usage for Control and Deceleration in Restricted Waterways," have been reported by W. McIlroy (1982). The scenario used in this experiment (and identical to that of the present study) presented an initial deceleration zone of 3/4 mile, leg 1, after entering from the ocean. This was then followed by a 45° turn. On emerging from the turn the ship can eventually be slowed down to a low speed midway between two gated buoys three quarters of a nautical mile along the third leg. The channel was 800 foot wide along the two straight legs and was widened in the turn to approximately twice that value. Twenty-four harbor pilots and twenty-four docking masters took part in the experiment. The harbor pilots did not have tugs available (except in the case of mechanical failures) whereas the docking masters had tugs available at all times. Two levels of tug horsepower were used (4000 and 8000 HP), each distributed between two and four tugs. Two ships were considered -- a familiar 80,000 DWT tanker and a less familiar 250,000 DWT tanker.

The overall shiphandling techniques were very similar in the two groups. Even though they had tug assistance at all times, the docking masters preferred to rely almost entirely on conventional controls (helm and engine rpm) to negotiate the turn and only used their tugs during the final stopping phase. This is the point where most difficulty was experienced under normal conditions due to the low speed of the ship, the strong port beam wind, the following current and the loss of rudder control effectiveness when engines are running in reverse to give maximum deceleration.

The tendency was to sail the larger ship at a higher speed in the first leg and in the turn, thereby minimizing the wind effects. In the final leg the

larger ship decelerated so that the mean speeds of both ships were comparable in that leg. The use of tugs with the 80,000 DWT ship was negligible, indicating that the pilots were capable of handling this ship size without tugs under normal conditions.

However, due to its higher speed in the turn and its much higher inertia the 250,000 DWT tanker required considerable tug assistance to safely decelerate in the final leg. Even when the available tug horsepower was doubled (to 8000 HP) the docking pilots still used approximately the same amount of tug moment as when half that power was available. Apparently this was recognized as being sufficient for adequately controlling the ship at this stage.

The report also introduced a new concept of "inherent risk" which accounted for ship speed, heading, turn rate, position in channel and channel *configuration simultaneously rather* than as separate measures. This concept considers the probability of grounding should a complete failure occur at each interval along the ship's track, and if recovery (equipment or tugs) cannot be effective within a selected time span (five minutes was chosen as an appropriate value).

For the 250,000 DWT tanker the "inherent risk factor" was large in the turn and in the first leg, due to both the higher speed of that ship and the limitations in the dimensions of the waterway and the channel elbow.

In addition to their normal runs all pilots experienced a complete engine and rudder failure (without recovery) just prior to entering the turn. They all had tugs present in the attendance mode. Tugs were defined to be in attendance when already attached to the ship at positions selected by the pilot and, therefore, available for control fairly rapid. This combined failure presented great difficulty to the majority of the pilots in this scenario, particularly with the larger ship and the lower tug horsepower. Even those pilots who successfully avoided grounding experienced considerable difficulty at various sections of the harbor during transit. There were large variations in the time lapse before pilots applied their tugs, and in this confined waterway such time delays were critical.

In the case of the 80,000 DWT tanker, groundings occurred principally in the final leg where the ship was susceptible to the strong beam wind and the following current. The 250,000 DWT tanker generally grounded in the turn. Because of its greater speed and greater inertia it did not respond sufficiently to the tug forces at either power level. Consequently, in most cases it failed to make the turn.

An "inherent risk" calculation predicted that this was to be expected, as it indicated that only a speed of under three knots in the turn would ensure safety after a complete failure. This risk of grounding is extremely sensitive to ship speed; a speed of four knots could result in 100% groundings.

A simultaneous rudder and engine failure without recovery has a very low probability of occurrence; yet, should it occur, the consequences could be serious in relatively confined waterways as indicated by this previous study. The probability of an engine failure alone or a rudder failure alone, with or without recovery in a finite time is much greater. The investigation described in this present report has considered these failure conditions on a 250,000 DWT tanker with 8000 tug horsepower available.

1.2 OBJECTIVES

A series of on-line experiments on tug usage have been planned for CAORF of which the present experiment is the second. These will be designed to obtain information on present techniques, to analyze the resulting performance using these techniques, to search for methods of improvement, and to develop optimal strategies, which can be incorporated in future training routines.

These experiments will be performed to determine the variability in pilot operating procedures for manipulating tugs in a restricted waterway when subjected to external environmental forces. These investigations will encompass the deceleration, stopping, turning and final berthing (and unberthing) phases of the operation, in addition to their use in assisting ships with impaired maneuverability.

The objectives of this series of experiments will be to establish requirements for the minimum number of tugs, their types, horsepower and method of attachment, in relation to ship characteristics and environmental factors. The present experiment is concerned principally with the effectiveness of two tugs with a total of 8000 HP in assisting a 250,000 DWT tanker following rudder and engine failure with or without recovery in a finite time.

CHAPTER 2

EXPERIMENT METHODOLOGY

2.1 EXPERIMENT DESCRIPTION

This present study represents the second of a three part investigation into tug usage in harbors. There are three essential phases in these tug operations.

1) Use of tugs for deceleration and control.

2) Tugs in emergency procedures.

3) Use of tugs for turning and berthing.

Tugs are required for this second operation and for safety reasons should be available at all times in restricted waterways in case of an engine/rudder failure which could inevitably end up in a collision, ramming or a grounding. If tugs are not already attached to the ship (in the attendance mode), but merely escorting the ship (in the assistance mode), the time lapse occurring after an emergency takes place and before they can become effective may be excessive so that a grounding cannot be avoided. Finite times are also required to remedy a rudder failure (at least three minutes) or an engine power failure (at least six minutes), so that again these efforts will be unable to save the ship. The safest technique is to limit the ship speed and provide tugs in the assistance mode at all times. The present experiment has as an objective to investigate the effectiveness of two tugs of 4,000 HP each, assisting a 250,000 DWT tanker in negotiati. a hypothetical harbor under realistic environment conditions. The study falls essentially into two phases: Phase 1, where the ship is maneuvered without any tugs being present, whereas in Phase 2, the ship has the two tugs in attendance at all times to reduce speed and effect the turning and final stopping maneuvers as desired. The requirement is made in both cases to be stopped relative to the ground at a point about 3/4 n miles outside the 45^{o} turn, in the presence of a strong wind and a flood current. Subjects were selected from the harbor pilots who participated in the previous experiment.

The experiment design is shown in Tables 2-1, 2-2(a), and 2-2(b).

In Group 1, 6 subjects conning a 250,000 DWT ship performed the experiment with no tugs in attendance. The pilots were permitted to use forward and/or reverse rpm for control and deceleration in attempting to stop at the assigned point on the channel centerline between buoys 11 and 12 (Figure 2-1).

The speed of the ship on entering the harbor from the sea outside (midway between buoys 3 and 4, Figure 2-1) was seven knots through the water in all cases.

A second group (2), comprising a further 6 subjects on the same 250,000 DWT ship performed the same task but in this case they had two 4,000 HP "Tina" type tugs in attendance at all times. In all cases the wind was gusting at 30 ± 10 knots and the direction varied $\pm 30^{o}$ about the 315^{o} point. The current was a following current of 1 knot strength, directed along the channel axis.

TABLE 2-1. EXPERIMENTAL DESIGN

Design Structure: 4 Factor Mixed Design
1 between Factor, 3 within Factors

Independent Variables Investigated:

C - Tug Assistance:	C_1	-	No Tugs
	C_2	-	Tugs
E - System Failed:	E_1	-	Engine
	E_2	-	Rudder
T - Time Course of Failure:	T_1	-	0 sec (no failure)
	T_2	-	Average Recovery (5 minutes for the rudder, 10 minutes for the engine)
	T_3	-	∞ sec (no recovery)
P - Position in Channel	P_1	-	Leg 1*
	P_2	-	Turn (Leg 2)*

* Failure will occur at any one of 4 positions in either channel segment, see Figure 2-2, which were randomly determined for each subject.

The total number of subjects = 12
Combination of E (E_1, E_2), T (T_1, T_2, T_3) and P (P_1, P_2) factors.

1 - $E_1 T_1 P_1$	<u>5</u> - $E_1 T_2 P_1$	<u>9</u> - $E_1 T_3 P_1$
2 - $E_1 T_1 P_2$	<u>6</u> - $E_1 T_2 P_2$	<u>10</u> - $E_1 T_3 P_2$
3 - $E_2 T_1 P_1$	<u>7</u> - $E_2 T_2 P_1$	<u>11</u> - $E_2 T_3 P_1$
4 - $E_2 T_1 P_2$	<u>8</u> - $E_2 T_2 P_2$	<u>12</u> - $E_2 T_3 P_2$

_ Designates Failure Run

TABLE 2-2(a). RUN ORDER - NO TUGS (C_1)

S_1	S_2	S_3
1 - RI - Turn - 2	1 - EI - Leg 1 - 2	1 - None
2 - EI - Leg 1 - 1	2 - RA - Leg 1 - 3	2 - None
3 - None	3 - EI - Turn - 3	3 - RI - Turn - 4
4 - None	4 - None	4 - EI - Leg 1 - 3
5 - EQ - Turn - 3	5 - None	5 - RA - Turn - 3
6 - RA - Turn - 1	6 - RI - Leg 1 - 1	6 - RA - Leg 1 - 2
7 - EI - Turn - 4	7 - None	7 - None
8 - EA - Leg 1 - 2	8 - EA - Turn - 4	8 - None
9 - None	9 - EA - Leg 1 - 4	9 - EI - Turn - 1
10 - RI - Leg 1 -3	10 - RI - Turn - 1	10 - EA - Leg 1 - 1
11 - None	11 - RA - Turn - 2	11 - RI - Leg 1 - 4
12 - RA - Leg 1 - 4	12 - None	12 - EA - Turn - 2

S_4	S_5	S_6
1 - None	1 - EA - Turn - 3	1 - RA - Turn - 2
2 - RA - Turn - 4	2 - None	2 - EA - Leg 1 - 1
3 - None	3 - RA - Turn - 1	3 - None
4 - RI - Turn - 3	4 - EI - Turn - 4	4 - EA - Turn - 4
5 - RA - Leg 1 -1	5 - RI - Leg 1 - 1	5 - EI - Turn - 1
6 - EA - Turn -1	6 - None	6 - None
7 - None	7 - RI - Turn - 2	7 - None
8 - EI - Turn - 2	8 - RA - Leg 1 - 4	8 - EI - Leg 1 - 2
9 - RI - Leg 1 - 2	9 - None	9 - RI - Turn - 3
10 - EI - Leg 1 -4	10 - None	10 - RA - Leg 1 -3
11 - EA - Leg 1 - 3	11 - EI - Leg 1 - 3	11 - None
12 - None	12 - EA - Leg 1 - 2	12 - RI - Leg 1 - 4

I = infinite time for recovery (T_3)
A = average time for recovery (T_2)
None = zero recovery time (no failure, T_1)

E = Engine (E_1)
R = Rudder (E_2)

Leg 1 = P_1
Turn = P_2

The final numeral defines the position of failure in leg 1 or the turn as indicated in Figure 2.2.

TABLE 2-2(b). RUN ORDER - TUG ASSISTANCE (C_2)

S_7	S_8	S_9
1 - EI - Turn - 2	1 - EA - Leg 1 - 3	1 - None
2 - None	2 - EA - Turn - 2	2 - RI - Leg 1 - 3
3 - None	3 - RA - Leg 1 - 1	3 - EI - Leg 1 - 2
4 - RA - Turn - 3	4 - RI - Leg 1 - 2	4 - RA - Leg 1 - 4
5 - None	5 - None	5 - EA - Leg 1 - 1
6 - EA - Leg 1 - 4	6 - RI - Turn - 1	6 - EI - Turn - 4
7 - RI - Leg 1 - 3	7 - EI - Leg 1 - 4	7 - RA - Turn - 1
8 - RI - Turn - 4	8 - None	8 - None
9 - RA - Leg 1 - 2	9 - None	9 - None
10 - None	10 - None	10 - EA - Turn - 3
11 - EA - Turn - 1	11 - EI - Turn - 3	11 - RI - Turn - 2
12 - EI - Leg 1 - 1	12 - RA - Turn - 4	12 - None
S_{10}	S_{11}	S_{12}
1 - RI - Leg 1 - 4	1 - None	1 - RA - Leg 1 - 1
2 - None	2 - EI - Turn - 2	2 - RI - Turn - 3
3 - EA - Turn - 1	3 - RI - Leg 1 - 1	3 - EA - Leg 1 - 3
4 - None	4 - EA - Leg 1 - 4	4 - None
5 - RI - Turn - 4	5 - None	5 - EI - Leg 1 - 4
6 - None	6 - EI - Leg 1 - 3	6 - None
7 - EA - Leg 1 - 2	7 - RA - Leg 1 - 2	7 - EA - Turn - 2
8 - RA - Turn - 2	8 - None	8 - RI - Leg 1 - 2
9 - EI - Leg 1 - 1	9 - EA - Turn - 4	9 - RA - Turn - 4
10 - EI - Turn - 3	10 - RA - Turn - 3	10 - None
11 - RA - Leg 1 - 3	11 - None	11 - None
12 - None	12 - RI - Turn - 1	12 - EI - Turn - 1

I = infinite time for recovery (T_3)
A = average time for recovery (T_2)
None = zero recovery time (no failure, T_1)

E = Engine (E_1)
R = Rudder (E_2)

Leg 1 = P_1
Turn = P_2

The final numeral defines the position of failure in leg 1 or the turn as indicated in Figure 2.2.

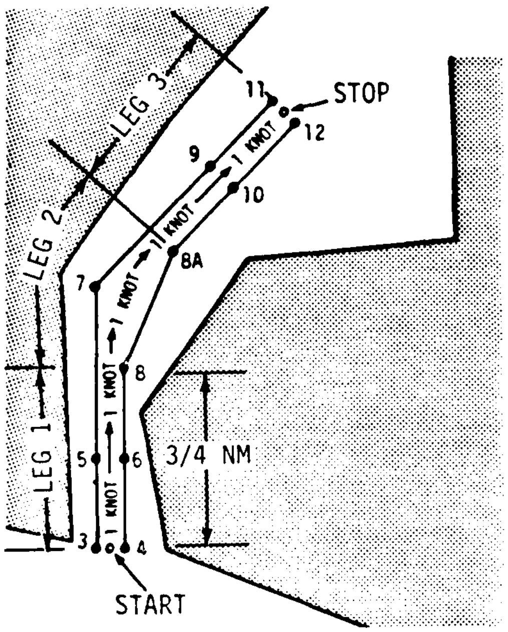


Figure 2-1. Harbor Configuration

The two groups were given a familiarization run without wind and current; this was designed to acquaint them with the ship characteristics, the scenario, navaids, etc.

Each subject then made a total of twelve runs with and without tugs (Group 2 and Group 1 respectively). They were subjected to failures of rudder or engine, but not in combination, either without recovery or with recovery after a finite time. At failure the rudder angle immediately becomes fixed at zero. A *five minute recovery period was used for the rudder failure and ten minutes for an engine failure.* In some runs they had no failure at all. These failures are more appropriate to actual life operations than the total rudder plus engine failure without recovery used in the previous experiment (McIlroy, 1982).

The failures were also designed to occur at eight specific points along leg 1 and in the turn as shown in Figure 2-2. The failures and their positions along with recovery were automatically controlled within the simulator.

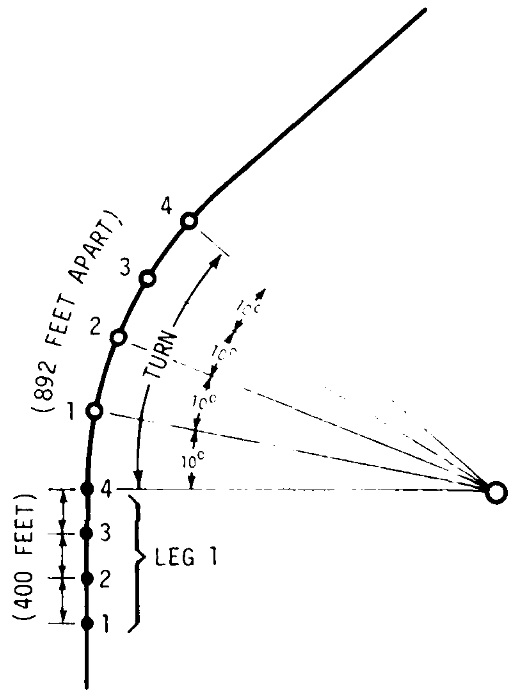


Figure 2-2. Location of Failure Points in Leg 1 and 45° Turn (Leg 2)

2.2 HARBOR DESCRIPTION

The simple channel configuration used in this experiment was identical to that used in a number of previous experiments. The spacings between buoys along the straight legs are uniformly 3/8 n mile. The channel is 800 feet wide along the straight legs and is

widened in the turn to approximately twice this value. The scenario was designed to simulate to some degree the harbor situation existing at Pelican Island in Galveston, and the suggested sequence of tug procedures adopted here follows the recommendations of Senior Galveston pilots for Pelican Island.

The scenario presents an initial deceleration zone of 3/4 n mile, leg 1, (after entering from the ocean at buoys 3 and 4) during which the ship can be slowed down progressively to about 3 or 4 knots in which time tugs can pass towing hawsers and safely lash up alongside the ship. This is then followed by a 45° turn (which represents both the recommended maximum heading change acceptable in a harbor waterway, and also a smooth transition curve radius of at least five times the length of the biggest ship using the channel, Bonafous (1977)). On emerging from the turn, the ship can eventually slow down to stop *midway between* the gated buoys 11 and 12, three quarters of a nautical mile (or approximately four or five ship lengths) along this third leg.

The first two buoys, 3 and 4, mark the entrance from the ocean at which point tugs can begin to hook up. It is not until 5 minutes later that the tugs can be used effectively. The harbor is assumed completely sheltered so that wave action can be neglected and therefore not incorporated in the simulation. A surrounding land mass was added to provide more realism to the exercise. The starting and finishing points are shown in Figure 2-1.

The water depths inside the channel and outside have been chosen so that the depth/draft ratio is 1.15, so as to give realistic harbor shallow water effects. The depth of water outside the channel section is adequate for safe operation of the selected tugs with their 9 foot draft.

The cross section of the channel is shown below in Figure 2-3. This represents a submerged channel. The relative dimensions of water depth inside (H) and outside ($H-H_1$, where ledge height = H_1) were selected so that the bank effect experienced by the ship would be about 38% of the bank effect it would experience in the presence of a fully emergent bank. This was determined based on Norrbin's reduction factor

$$\text{Reduction Factor} = e^{-2H_1/(H-H_1)}$$

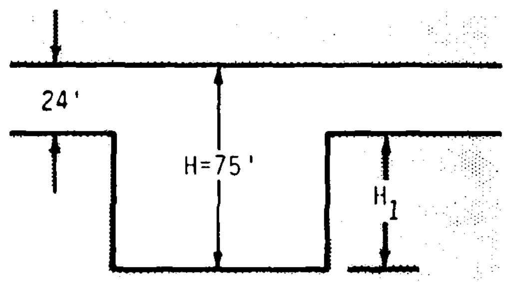


Figure 2-3. Channel Cross Section

2.3 ENVIRONMENTAL CONDITIONS

2.3.1 Wind. The wind in the harbor was assumed to be gusting with a strength of 30 ± 10 knots from the NW approximately (315° ± 30°). The time record of wind speed and direction is shown in accompanying Figure 2-4.

With the wind blowing from NW, the wind force will tend to decelerate the ship in the first leg, thus making it easier to slow down prior to the turn. However, luffing into the wind in the turn and in the final leg will make it

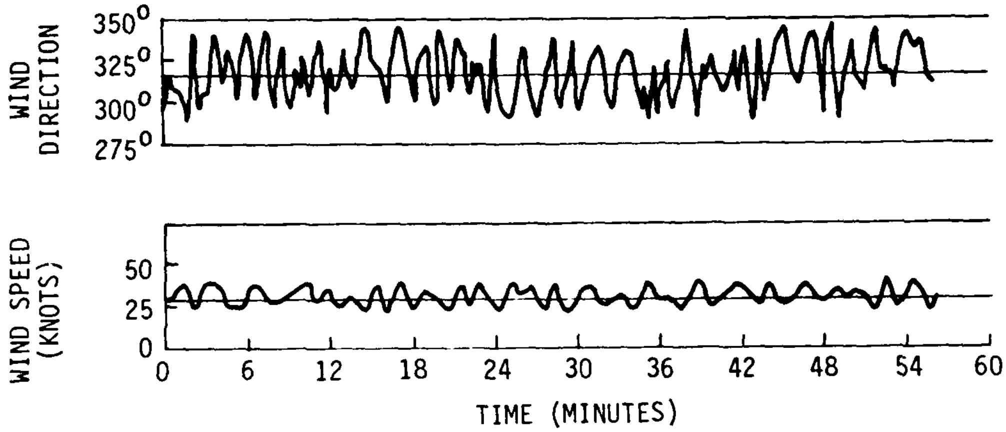


Figure 2-4. Time Variation in Wind Strength and Direction

more difficult to turn at low speeds, and cause the ship to drift to starboard with its bow swinging to port as it decelerates. This will be accentuated by the presence of the following current.

2.3.2 Current. A flood current was assumed to flow in the channel direction at 1 knot speed. In the 45° turn it flows along the transition arc of radius 5,100 feet, which is tangential to the centerline of leg 1 and leg 2 at the buoy locations 8 and 8A respectively. The flow in the corner and at the cut-off were assumed to be separated and eddying and not contributing significantly to the overall water transport along the channel. On this basis, the current direction was changed in discrete steps to 7-1/2°, 22-1/2°, 37-1/2° and 45° at points A, B, C and D respectively as shown in the Figure 2-5.

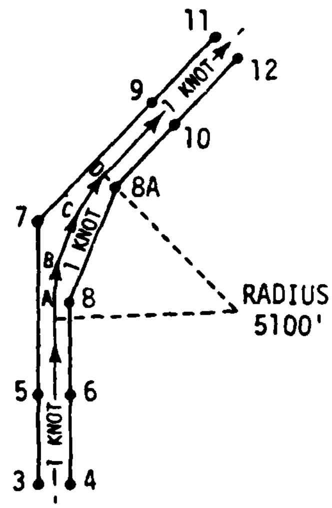


Figure 2-5. Current Intensity and Direction

2.4 SIMPLIFIED TUGBOAT SIMULATION

Three methods of attachment are possible:

1) Towing on line.
2) Pushing against the ship's hull.
3) Tugs lashed alongside.

A specific force is applied to Ownship in a specified direction relative to Ownship axis. The force input is designated as a fraction of the maximum bollard pull force available from the tug, according to the following schedule, Table 2-3.

TABLE 2-3. TUG ENGINE SPEED/FORCE

Tug Order	Tug Force Function
Full Ahead	1.00
Half Ahead	0.50
Slow Ahead	0.25
Dead Slow	0.10
Stop	0

2.4.1 Attachment Points

The locations on Ownship's hull where the tugboats can be attached are defined in Figure 2-6. Three are located on each side of the ship, and one at the stem and one at the stern. A maximum of six tugs can be used (designated tugs 1 through 6 in the datalog) and placed at any of these eight positions designated. In this experiment, however, only two tugs were employed. The bow and quarter locations are one-third of a ship length forward and aft of the athwartship axis through the center of gravity. The location of the tug attachment point, when the tug is at the end of a towline, relative to the ship's centerline (y_{TRi}) is also listed in the simulation set-up tape (SST). When the tug is alongside y_{TRi} will be equal to 1/2 (ship beam + tug beam).

The maximum thrust ($TMAXF_i$) is the maximum value that can be applied by the given tug at the attachment point. The thrust direction ($TUGFPS_i$) is the direction of the applied thrust relative to the ship's axis, as shown in the diagram below (Figure 2-7).

The applied thrust is equivalent to the thrust force fraction (TFF_i) times the maximum possible thrust ($TMAXF_i$).

Since there is a time delay between when the tug thrust and/or direction is commanded, and when it is actually attained by the tug, the model simply accounts for the variation, a

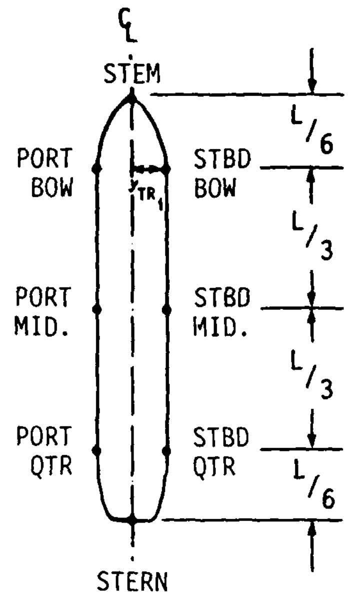


Figure 2-6. Notation for Tug Positioning

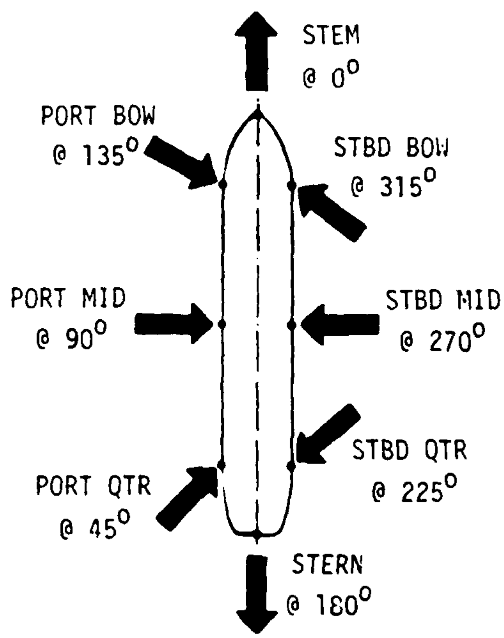


Figure 2-7. Convention for Tug Orders

linear build-up, in thrust and direction during this time period.

The commanded thrust, T_{C_i},

in direction $\psi_{C_i} = T_{max} C_i$,

where C_i = force fraction.

Then the time variation of thrust

and direction are

$$T_i = T_{(n-1)_i} + \alpha_1 (T_{C_i} - T_{(n-1)_i})$$

and

$$\psi_i = \psi_{(n-1)_i} + \alpha_2 (\psi_{C_i} - \psi_{(n-1)_i})$$

when $0 \leq \alpha_1 \leq 1$ and $0 \leq \alpha_2 \leq 1$;

Thereafter $T_i = T_{C_i}$ and $\psi_i = \psi_{C_i}$

The dimensionless time factors α_1 ($= \Delta t/\tau_1$) and α_2 ($= \Delta t/\tau_2$) are derived from the time in seconds that has passed since the order was inserted in the simulator (Δt) and the corresponding time constants τ_1 ($PROPTC_i$) and τ_2 ($TFDTC_i$) for thrust and direction, respectively, in seconds.

An active tug will consequently interact with Ownship in the specified mode (thrust and direction) and at the assigned attachment point as specified above.

For tugs lashed alongside, the effective lever arm for determining the moment on the ship is 1/2 (ship beam + tug beam). Relative to the ship length this fraction is denoted by BT_i in the simulation.

The forces and moments resulting from the tugs are, for each tug:

$$X_{t_i} = T_i \cos \psi_i$$

$$T_{t_i} = T_i \sin \psi_i$$

and $N_{T_i} = Y_{t_i} l_{t_i} - X_{t_i} (B/2)$

where l_{t_i} = distance of tug i from the ship's center of gravity measured along the centerline of the ship.

For a tug pulling on a towline the moment will be

$N_{t_i} = Y_{t_i} l_{t_i} - X_{t_i} y_{tRi}$, rather than the above.

The total forces and moments exerted by the tugs on the ship are simply the addition of the individual contributions.

Since the subjects tend to issue orders with tugs pushing or pulling at the starboard and port positions perpendicular to the centerline of the ship, it is convenient for the control station operators to insert directions of 270° and 90° respectively, and then use positive and negative values for the thrust fraction for pushing and pulling. For example, a full ahead thrust at starboard bow corresponds to a positive thrust factor of one and 270° direction. On the other hand, a full astern pull at the same point corresponds to a negative thrust factor of minus one, but with the same direction.

2.5 OWNSHIP AND TUG CHARACTERISTICS

A large 250,000 DWT tanker was used as Ownship in these experiments. It represents a ship of very large tonnage familiar to only a few pilots in U.S. waters. Its characteristics are tabulated in Table 2-4.

TABLE 2-4. OWNSHIP CHARACTERISTICS

	250K Tanker
Length (L)	1,085 ft.
Draft (T)	65 ft.
Beam	170 ft.
Depth/Draft	1.15
Ahead HP	36,000
Prop. Dia.	29.2 ft.
Max. Rudder Angle	35^o
Rudder Area (A_R)	1,302 $ft.^2$
Rudder Area Ratio (A_R/LT)	0.018

The following simulations were available for the ship and were used during these experiments:

1) *Zero/low speed hydrodynamics.*

2) Aerodynamics.

3) Shallow water effects.

4) Bank effects.

However, squat and modified trim in restricted shallow waters and wave forces (all of which would be small in this scenario) were not included in the simulation.

2.5.1 Tug Simulation

For the present experiments the "simple" tug simulation option on the advanced tug simulator was employed. This permitted specific information on the forces and moments exerted by each tug to be recorded directly on the summary datalogs. Fortunately the assumptions implied in using this simplified form (constant thrust and angle of application independent of ship speed, tug capabilities, etc.) could be used with some confidence based upon the results of the sea-trials involving the "Tina" (a 1,000 HP tug with 360° steerable propulsion units and Kort nozzles) and the 25,000 DWT USNS "Yukon." These tests were performed to measure static and dynamic bollard pulls at angles to the ship's centerline while the ship and tug were proceeding at speeds from zero to six knots, in addition to the tug's effectiveness when trailing and pulling with astern thrust. An examination of the data indicated that if a maximum bollard pull of a constant 27,000 pounds were adopted independent of ship speed (but less than 6 knots), hawser angle and propulsion unit angle, the maximum error would never exceed 10%. Such an assumption was ideal for our purposes, and consequently tugs with "Tina's" characteristics were built into the present experiment. In addition, this same tug with its hydrodynamics and aerodynamics etc. was to be used initially in the advanced tug simulator. During the initial verification and validation phases of this advanced tug model the appropriateness of the simple model used here would become apparent. The characteristics of the "Tina" tug are tabulated in Table 2-5.

These tugs can contribute maximum thrusts of the order of 27,000 pounds on a continuous basis at any heading and hence, without the tug having to be repositioned, control of Ownship can be maintained at all times. Full thrust can be obtained aft and broadside as well as forward, which permits a minimum amount of line handling while docking.

The magnitude of horsepower to be assigned to the tugs in this experiment was determined after closely examining literature dealing specifically with

TABLE 2-5. CHARACTERISTICS - WILMINGTON LAUNCH TUG TINA

Length Overall	65.0 ft.
Beam, Molded	26.0 ft.
Draft, Molded	9.0 ft.
Draft to Bottom of Skeg	10.5 ft.
Displacement (Design)	127.5 tons
Brake Horsepower	1,000 HP

Propulsion. Two diesel engines coupled to Murray and Tregurtha 360-degree steerable propulsion units with propellers in Kort nozzles. The two propellers are mounted aft. The tugboat is designed to operate as a tractor tugboat when going astern.

Propellers. Right-hand, four-bladed, Kaplan type; 5.33 feet diameter in a Kort nozzle.

actual tug operations throughout the world (e.g. National Ports Council, 1977), and also based on observations during the previous experiment of this series.

There appeared to be an extremely wide variation in specifications for the required total tug horsepower as related to ship size. Based on the available information, and a formula based on testing at NMI in the UK, a total bollard pull of 50 tons was initially considered appropriate for the maneuvers in this experiment. However, following the findings of the first experiment of the series (McIlroy, 1982), twice this value was used in this experiment. Earlier it had been found that even with this horsepower (8000 HP) available the 250,000 DWT tanker could not be prevented from grounding in a majority of the runs, due to its excessive speeds. In the deceleration phase in the final leg, however, the pilots only used the tugs at a lower power level which they considered adequate for the purpose. As a consequence, two 4,000 HP tugs of the "Tina" type were incorporated in the present design.

The two tugs could either be attached at the bow and the stern on soft lines, or be free to push against the ship hull at attachment points initially assigned by the pilot on first entering the channel.

In order to have a more realistic simulation of the real world conditions in these experiments a five minute time delay was imposed after entering the channel before the tugs could become effective. In addition, for a tug attached at a given point on the ship there was a time delay of one minute between the time an order is given by the pilot and when it is effectively carried out by the tug (i.e. τ_l = 60 secs). If a tug is moved from one attachment point to another on the opposite side of the ship a further 2 minute delay occurred; if moved from one attachment point to another on the same side, this delay was one minute.

2.5.2 Tug Display

In general, during the simulation exercises the pilot is at a disadvantage in that he cannot check tug locations by peering out of the wheelhouse. Therefore he must remember which tugs were active and which were inactive, as well as at what power levels they were operating. To compensate for this deficiency the pilot was presented with a display of the ship's planform and the relative tug positions using a closed-circuit TV monitor, Figure 2-8.

At the control station a white magnetic board, approximately 2 ft. x 1-1/2 ft., had a black planform of the ship superimposed. In addition, active tugs were represented by black arrows with the arrowhead indicating the direction of thrust. If the tug was on a towline, the arrow would be displaced from the ship hull; if it was alongside or pushing, the arrow would be adjacent to or abut the hull. The angle of application of thrust was shown by the arrow's direction.

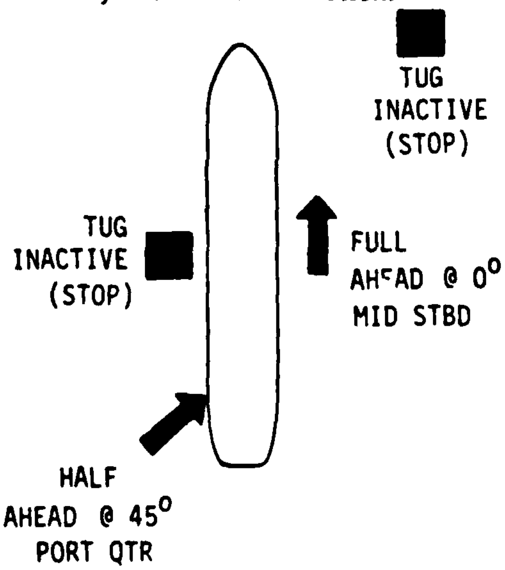


Figure 2-8. Tug/Ship Configuration as Displayed to Pilot

"Inactive" tugs are represented by small black magnetic squares, situated approximately in their last active positions relative to the ship. These arrows and squares were moved by one of the control operators when the pilots' orders were carried out at the control station.

The pilot was also provided with a diagram indicating the tug attachment points that are available (Figure 2-6), in addition to the proposed format for commanding tug forces and directions (Figure 2-7). This format was discussed with the pilot prior to his runs. At the same time he also explained his personal conventions for issuing orders, so that an accurate interpretation could be made by the control operators.

Engine orders were performed in the telegraph mode.

2.6 TEST SUBJECTS

The twelve pilots who participated in this experiment were drawn from the harbor pilots who took part in the previous experiment on Tug Usage for Control and Deceleration (McIlroy, 1982), but had not been involved in the runs with the 250,000 DWT tanker. They comprised six pilots from New York and six pilots from Delaware.

They were, therefore very familiar with the harbor and environmental effects (on the smaller ship) but not accustomed to this larger ship.

2.7 PRELIMINARY OPERATIONS

Before performing his experimental runs, the pilot was briefly introduced to the CAORF bridge and its equipment, the properties of the visual scene and the specific procedures that

would be used. A mate (a member of the CAORF Operations staff) was present to respond to any questions the pilot might have concerning the ship. The pilot was shown the signal telegraph control and informed that bridge control would be used during the experiment; his engine orders would be executed by his mate, who would also monitor and record his helm and tug orders (where appropriate) during the experimental runs.

The pilot was then briefed by a member of the CAORF staff who discussed the scenarios, channel dimensions, banks, shallow water, winds and currents, ship and tug characteristics, (where appropriate), operating procedures and requirements. He was then provided with a chart of the harbor and a detailed printed booklet duplicating the details of the verbal briefing. The pilot could therefore refer to this document and chart at any time during the experiment should he have any questions. He was told he would perform thirteen runs in all, the first for familiarization and then twelve subsequent runs. He was not told at any time when and where to expect mechanical failures.

The first of his experimental runs was designed to familiarize the pilot with the harbor scenario, the navaids and the ship which he would use throughout his series of runs. During this familiarization run, performed in the absence of external environmental influences, the objectives were identical to the following runs; namely to be stopped relative to ground at the end of leg 3.

At the end of each run a short informal briefing was held with each subject by a member of the CAORF Research staff. Questions regarding the subjective reactions to the run, vessel handling, wind and bank effects, tug handling qualities, etc., were explored.

At the end of the series of twelve runs a final debriefing session was held to obtain an overall assessment of the experiment from the pilot and indications of where in his judgement certain aspects may have lacked realism.

2.8 DATA COLLECTION

A variety of sources were used for data collection during the running and analyses of the experiment. The major performance measures were obtained or derived from computer summary datalogs, ship's bridge data sheets, and debriefings. The primary source for all objective data during the actual experiment runs was the "playback tape." This is a magnetic recording of each run, taken at a fixed time interval, of important computer and ship state parameters (numbering well over 1,000 items). The recording rate for the experiment was once every 10 seconds.

2.9 COMPUTER SUMMARY DATALOGS

Computer summary datalogs are printouts from the playback tapes. This information was made available as hard copy printouts at the end of groups of runs. A listing of the 64 items obtained on the printouts and used in the subsequent analyses is shown in Table 2-6.

2.10 DATA PRESENTATIONS

Data collected during the experiment are presented in the following format for visual interpretation and qualitative evaluation that will complement

TABLE 2-6. COMPUTER SUMMARY DATALOGS

IDENTIFIER	Playback Tape Number
TIME	Time Step Number Bridge Time (hr:min:ss)
HYDRODYNAMICS	X-Axis Hydrodynamic Hull Force (lb/10) Y-Axis Hydrodynamic Hull Force (lb/10) Hydrodynamic Moment (lb-ft/10)
WIND	Actual Wind Speed (knot) Actual Wind Direction (degrees) Aerodynamic Force X-Axis (lb/10) Aerodynamic Force Y-Axis (lb/10) Aerodynamic Yaw Moment (lb-ft/10) Relative Wind Direction (degrees) Relative Wind Speed (knots)
DEPTH	Water Depth
O/S SPEEDS	O/S Heading (degrees) O/S Fore and Aft Speed (ft/sec) O/S Athwartship Speed (ft/sec) O/S Velocity North (knot) O/S Velocity East (knot) O/S Ground Speed (knot) O/S Resultant Speed (ft/sec)
BANK EFFECTS	O/S Centre Distance to Bank/Channel (nm) Channel/Bank Interaction Y Force (lb/10) Channel/Bank Interaction Moment (lb-ft/10)
WATER CURRENT	Water Current Speed, Checkpoint 1 (ft/sec) Water Current Direction, Checkpoint 1 (degrees) Water Current Speed, Checkpoint 4 (ft/sec) Water Current Direction, Checkpoint 4 (degrees)
O/S LOCATION	O/S North Coordinate (nm) O/S East Coordinate (nm) O/S North Bridge Coordinate (nm) O/S East Bridge Coordinate (nm)
PROPELLER	#1 Engine Propeller Revs (rpm) #1 Engine X-Axis Propeller Force (lb/10) #1 Engine Y-Axis Propeller Force (lb/10) #1 Engine Propeller Moment (lb-ft/10)

TABLE 2-6. COMPUTER SUMMARY DATALOGS (CONT)

RUDDER	Rudder Angle (degrees) Rudder X-Axis Force (lb/10) Rudder Y-Axis Force (lb/10) Rudder Yaw Moment (lb-ft/10)
SHIP ACCELERATIONS	O/S Fore/Aft Ship Acceleration (ft/sec^2) O/S Athwartship Ship Acceleration (ft/sec^2) O/S Yaw Acceleration (radian/sec^2)
COMBINED NON-HYDRO EFFECTS	X-Axis Combined Forces (non-hydro) (lb/10) Y-Axis Combined Forces (non-hydro) (lb/10) Combined Moment (non-hydro) (lb-ft/10)
TUG LONGITUDINAL FORCE, X_T	Tug Position 1 X-Axis Force (lb/10)* Tug Position 2 X-Axis Force (lb/10) Tug Position 3 X-Axis Force (lb/10) Tug Position 4 X-Axis Force (lb/10) Tug Position 5 X-Axis Force (lb/10) Tug Position 6 X-Axis Force (lb/10)
TUG LATERAL FORCE, Y_T	Tug Position 1 Y-Axis Force (lb/10) Tug Position 2 Y-Axis Force (lb/10) Tug Position 3 Y-Axis Force (lb/10) Tug Position 4 Y-Axis Force (lb/10) Tug Position 5 Y-Axis Force (lb/10) Tug Position 6 Y-Axis Force (lb/10)
TUG YAW MOMENT, N_T	Tug Position 1 Yaw Moment (lb-ft/10) Tug Position 2 Yaw Moment (lb-ft/10) Tug Position 3 Yaw Moment (lb-ft/10) Tug Position 4 Yaw Moment (lb-ft/10) Tug Position 5 Yaw Moment (lb-ft/10) Tug Position 6 Yaw Moment (lb-ft/10)

* Tug Positions are indicated in Figure 2-6.

the conclusions of the statistical analyses of the same data.

o Ship track plots, derived from the ship's dimensions, the coordinates of the its center of gravity (X_o, Y_o) and its heading as recorded in the data summary at two minute intervals.

This was done for 156 runs, and is presented in two groupings:

1) Twelve familiarization runs.

2) Twelve subsequent runs per subject involving no failures, rudder, and engine failures as

indicated in Table 2-2. The type and location of the failure are indicated on each figure.

- Simultaneous plots of rudder angle, rudder moment and engine speed variation with time over the duration of runs, for both the active and no tug modes. These data are obtained directly from the data summary. For the active mode these quantities are shown along with the corresponding plots of tug forces X_T and Y_T and tug moment N_T.

- Simultaneous plots of tug forces and tug moments are presented for the active tug group, 72 plots in all. The data for these plots were obtained directly from the information in the summary datalogs. In the previous experiment (McIlroy, 1982) the same data had to be derived from the combined nonhydrodynamic forces and moments and the individual values for wind and banks.

- Plots indicating the mean distance off the assigned track (the centerline in legs 1 and 3, and the transition arc in leg 2) at 400 feet intervals. The individual values of distance off track were calculated from the ship coordinates at the interpolated time corresponding to each 400 foot increment using the information in the data summary. The data corresponding to the subjects in each combination of factors considered, for example, type of failure (engine, rudder), time course of failure (no failure, average recovery time, no recovery), failure position (leg 1, turn), and tug mode (no tugs, active tugs), were then averaged to obtain the mean distance off-track at that location. At the same time the standard deviation and the extremes of these individual measurements were estimated. The mean, standard deviation and the extremes are all depicted on the plots. The extent of each leg is indicated on the horizontal axis, where for convenience the circular arc has been straightened. It should also be noted in these plots that the actual channel width in leg 2 is greater than the nominal 800 feet in each of the other legs. The variation in width is shown in Figure 3-27, in section 3.1.5 and should be taken into consideration when visually evaluating the closeness to grounding.

2.11 NEW PERFORMANCE MEASURES

A new set of performance measures was introduced in the previous report on Tug Usage for Control and Deceleration in Restricted Waterways (McIlroy, 1982). The discussion is repeated here for completeness.

Performance has conventionally been measured in terms of the RMS deviations off an assigned track and the RMS rudder angle that was used. The RMS deviation off-track of the ship's center of gravity, however, must be considered in conjunction with the swept path to indicate the closeness of the ship's extremities to the channel boundaries. In itself it does not give a measure of the nearness to grounding. The RMS rudder angle indicates the amount of rudder that was used to perform the transit, and consequently the amount of rudder that remains to control the ship should an emergency situation arise. Again this measure in itself is not sufficient. The amount of rudder moment that can be exerted by

the ship is dependent not only on the amount of rudder but also the rudder efficiency; the rudder efficiency is a function of hull speed and engine speed, and importantly the direction of propeller rotation. This is demonstrated very clearly in the time histories of rudder moment, rudder angle and engine RPM (Figures 3.14 and 3.25). In these figures it can be seen that in the final deceleration stages of leg 3, although the engine is going full astern and the rudder angle is saturated, due to the ship's low speed the actual rudder moment is very small compared to its values at prior times. That is, as the ship decelerates, it effectively loses all its rudder control efficiency. It would therefore be more realistic to adopt a performance measure of RMS rudder moment or RMS "effective" rudder angle to account for not only actual rudder angle but also the ship's hull speed and engine speed during the transit. As a consequence of these considerations a new concept of a combined performance measure was adopted to account for the interaction of all the ship's state and control variables. This new measure or performance index will be denoted by J and will contain

a) effect of rudder and deviation off-track
b) "inherent" risk
c) tug moment

(a) The contribution of rudder is the mean value of the sum of the squared rudder angles normalized with respect to the maximum rudder angle, 35°. That is,

$$^{1}/_{T} \int_{0}^{T} (^{\delta}/_{35})^2 \, dt, \text{ or}$$
$$(^{\delta RMS}/_{35})^2$$

The contribution of deviation off-track likewise, is the sum of the squared deviations normalized with respect to a bias value of 100 feet. It was considered that pilots would be quite satisfied with their performance if their ship lay within 100 feet either to the left or right of the designated track, and would not necessarily make any effort to return the ship exactly to the track. Especially in the presence of wind they may prefer to lie to windward. The subsequent experiment tended to justify this value.

Hence deviation off-track contribution

$$= {}^{1}/_{T} \int_{0}^{T} (^{y}/_{100})^2 \, dt \text{ or}$$
$$(^{yRMS}/_{100})^2$$

These two contributions to J do not tell the complete story, for they indicate that a low value of the performance index, indicating good performance, can be achieved by travelling at higher speeds. Higher ship speeds increase the rudder efficiency, decrease the rudder angle requirement, minimize the wind influence and produce better trackkeeping. However, this does not consider the possibility of mechanical failures taking place at any time. In this case, it would be preferable to be travelling at low speed, contrary to the above conclusion! To include the possibility of a failure at any point along its track and the "inherent" risk of grounding, the following concept was developed.

(b) The vulnerability of the ship at any instant is a function of the state and the actual position of the ship -- its location, heading, turn rate, speed, its dimensions and the contours of the boundaries of the waterway. Should a failure take place at any instant, the time ("recovery time") before the failure can be corrected or before tugs can restore the ship to follow a safe track and prevent grounding is an extremely important factor. In the

subsequent analysis three values for recovery time were assumed -- 2-1/2, 5 and 10 minutes respectively.

From the state of the ship and its position at each time interval during the passage the velocity and direction of the stern and the stem were calculated assuming, for simplicity, that the ship may be represented as a straight line. This assumption can be easily corrected to account for the ship's actual hull form. Now assuming that the ship's speed and direction remain unchanged following the failure its trajectory can be calculated and the shortest time for the first impact on the surrounding boundaries estimated. In this way the "inherent risk" of grounding can be established. If the time for the ship to strike the nearest boundary is less than the recovery time then a grounding will take place and a value of unity will be assigned for this time. Conversely, if the impact time is greater than the recovery time a zero value is assigned to the risk. In this way corresponding to each point along the ship's trajectory a value can be assigned, either 0 or 1, which are then accumulated in time. The ratio of the number of grounding possibilities and the total time in the channel section represent the percentage of time the ship is in danger of grounding should a failure occur. This has been denoted in the subsequent analysis by α_1, α_2, or α_3 (depending on the values assigned to the recovery time). This is an important addition to the performance index as it is speed dependent. Even when the ship is perfectly on track, there is always an inherent risk if the speed exceeds a certain limit when negotiating turns in restricted waterways. This is illustrated by a simple calculation (Appendix D) which shows that in the present scenario the inherent risk in the turn is zero only if the speed is maintained at 3 knots or lower (based on a five minute recovery time).

When tugs are also being used for controlling the ship, the state and position of the ship is dependent on the prior tug usage. However, any assistance from the tugs following a failure is not accounted for in the calculation of α. Some time will elapse before they can effectively divert the ship's path, and their effect on inherent risk will be principally in reducing the recovery time. Sample off-line calculations (Appendix C) demonstrate the influence of instantaneous tug assistance on the advance and transfer of the ship following failure.

(c) When tugs are being actively used for controlling the ship, an additional tug contribution is added to the performance index, namely $(\text{RMS } N_{TUG}/N_{MAX\ TUG})^2$. This is similar to the rudder contribution, and represents the degree to which tugs are being used in controlling the ship relative to their full potential. Similarly it also provides a measure of the amount of tug moment remaining that is available when needed.

The maximum tug moment is produced when half the tug power is applied at the forward attachment point (1/3 length ahead of the center of gravity) and the other half at the aft attachment point (1/3 length behind the center of gravity) but in the opposite direction. For the tug used in this study a maximum bollard pull of 27 lb. per tug BHP was used. Consequently if P = tug horsepower

$$N_{TUG\ MAX} = 9\ PL.$$

Only tug moment was included in the performance index since we are mainly concerned with control. No

consideration has been given to the lateral and longitudinal forces that produce these moments, but which in themselves play an important role in maintaining the ship on a safe track, particularly during the final deceleration stages of leg 3.

The final representation of the performance index J used in the subsequent analysis is

$$J_L = \alpha_i + \left(\frac{Y_{rms}}{100}\right)^2 + \left(\frac{\delta_{RMS}}{35}\right)^2 + \left(\frac{N_{TUG\ RMS}}{N_{MAX}}\right)^2$$

where index i (=1, 2, 3) refers to the assumed recovery times (2-1/2, 5, 10 minutes) respectively.

In this investigation the mean lateral and longitudinal tug forces normalized with respect to the maximum possible (27P) have been included as additional measures in the statistical analysis. The importance of these tug forces was apparent in the previous analysis, expecially during the final phase of leg 3.

2.12 ANOVA ANALYSIS

The statistical analysis of the experiment was carried out using the Analysis of Variance on each of the performance measures under consideration.

The Anova was performed on each of the seventeen measures listed below. Table 2-7 shows the resulting main analysis source table. It indicates the significant main effects and interactions (up to the fifth order) to significance levels of p = 0.001, 0.01 and 0.05 respectively denoted by the cross, circle and square in these charts. Not all measures are discussed in detail in this report.

The independent variables are defined as follows:

C = Tug Mode (No tugs or tugs active)

D = Replicate Run Number (Run 2, Run 3 or Run 4)

E = System Failed (engine or rudder)

T = Time Cource of Failure (no failure, average recovery time, no recovery)

P = Position in Channel where Failure Occurs (leg 1 or turn)

L = Leg Number (leg 1, turn (leg 2), or leg 3)

The performance measures investigated were:

- o % time for left rudder
- o % time for right rudder
- o Total time the rudder was used

* Left and right rudder contributions were only considered if $|\delta| > 3^o$, as smaller angles (jitter) can be attributed to the helmsman and do not contribute to the ship control.

The total time during which rudder was used is the mean value per leg, i.e., the total time during the complete transit divided by three (three legs).

- o Mean Swept Path (ft)
- o Performance Index J_1
- o Performance Index J_2
- o Performance Index J_3
- o Risk Factor α_1

- o Risk Factor α_2
- o Risk Factor α_3
- o Contribution of distance off-track to J

  $= (\frac{Y_{RMS}}{100})^2$
- o Contribution of rudder to J

  $= (\delta_{RMS}/35)^2$
- o Contribution of tug moment to J

  $= (\frac{N_{TUG\ RMS}}{N_{TUG\ MAX}})^2$
- o Mean longitudinal speed in leg (ft/sec)
- o The normalized mean longitudinal tug force, $\overline{X}_T$,

  $= (\frac{X_{TUG\ MEAN}}{X_{TUG\ MAX}})$
- o The normalized mean lateral tug force, $\overline{Y}_T$,

  $= (\frac{Y_{TUG\ MEAN}}{Y_{TUG\ MAX}})$

TABLE 2-7. ANOVA SOURCE TABLE

PERFORMANCE MEASURE	C	E	T	P	L	CE	CT	ET	CP	EP	TP	CL	EL	TL	PL	CET	CEP	CTP	ETP	CEL	CTL	ETL	CPL	EPL	TPL	CETP	CETL	CEPL	CTPL	ETPL	CETPL
	SOURCE																														
% TIME LEFT RUDDER		○	x		x			x					○									x		□							
% TIME RIGHT RUDDER		x	x	□				x		○	○		○	□								x		○	x						
TIME RUDDER USED (MTS)		x	x		x			x			○		x	x			□	□				x		x	x						
SWEPT PATH (FT)		□	○		x			□					○	x							□	□									
J_1			□		x									○					□					□							
J_2			□		x									○										□							
J_3			□		x									x																	
$\alpha 1$		x	x		x	○	x	□	□	○	□		○	x	□	□	□		x	□	○	○	□	○		○	○			x	
$\alpha 2$			○		x	○	x		○				x	x	x	○	○		□	□	□	x	□	x	□		x			x	
$\alpha 3$	□	□	x		x	○	x					○	x	x		x			□	□	○	x		□			x			x	
DEVIATION-OFF-TRACK CONTR$^{\underline{N}}$			□		x									○																	
RUDDER CONTRIBUTION		x	x		x	□		x					x	○	□			□				x		x	□		□				
TUG MOMENT CONTRIBUTION	x	x	x	○	x	x	x	x	○	○	○	x		□	x	x	○	○	x		□		x	x	□	x			□	□	
MEAN SPEED		x	x	x	x	x		x		x	x		x	x	x	x			○	x	○	x		x	x		x	□			
LONGITUDINAL TUG FORCE, X_T	x		□		○		□	○				○			x	○						x	x				x				
LATERAL TUG FORCE, Y_T	x	□	x		x	□	x	○			□	x		○	x	○		□			○	□	x				□				

x p < 0.001
○ p < 0.01
□ p < 0.05

C = TUG ASSISTANCE MODE (NO TUGS/TUGS)
E = *SYSTEM FAILED (ENGINE/RUDDER)*
T = TIME COURSE OF FAILURE (NO FAILURE, AVERAGE RECOVERY, NO RECOVERY)
P = POSITION OF FAILURE (LEG 1/TURN)
L = LEG NUMBER

CHAPTER 3

RESULTS AND DISCUSSION

The data collected during this study were examined in two ways: qualitatively by visual examination of simultaneous plots of ship tracks and the corresponding control activity, and quantitatively by statistical methods.

3.1 QUALITATIVE ANALYSIS

This section describes the results of the qualitative approach. The statistical approach is presented later in Section 3.2.

3.1.1 Observations on Non-Failure Runs

Each pilot had four non-failure runs (in addition to his initial familiarization run) in his program interspersed among the failure runs in a random manner, as shown in Table 2-2. Consequently there resulted twenty-four runs by pilots who did not have any tug assistance and twenty-four more runs where tugs were available and could be used as desired. As stated in Section 2.6 the test subjects in this experiment were harbor pilots who had participated in the previous study but only on an 80,000 DWT tanker and without tug assistance until they experienced the complete mechanical failure. The data were studied by observing ship tracks, rudder and rpm variations and tug forces and moments (where appropriate) and comparing the techniques of the pilots.

3.1.1.1 Ship Ground Tracks

The ship ground tracks for the initial familiarization run are shown in Figures 3-1 (a) and 3-1 (b). For each subject his twelve subsequent runs are presented in the order they were performed (Table 2-2), R1 to R12, in Figures 3.2 to 3.13. The legend attached to each indicates the failure condition, the time course of failure, the leg in which the failure occurred and finally the position within that leg. As shown in Table 2-1, the average time for a rudder failure was five minutes, and for the engine failure ten minutes. The first six subjects (S1 to S6) did not have tug assistance, whereas the remaining six (S7 to S12) had two tugs available giving a total of 8000 BHP maximum. The two groups are labeled "no tugs" and "tugs active" respectively.

The ground tracks show the ship planform and the rudder setting at two minute intervals, and the ship's position relative to the boundaries of the channel.

The pilots generally had little difficulty in completing a successful passage with the 250,000 DWT tanker, a conclusion also reached in the previous investigation. It is only in the final deceleration phase that tug assistance may be desireable, to counteract drift and moments due to the beam wind and following current.

As pointed out previously the use of reverse engine power to provide deceleration greatly reduces the rudder effectiveness for which tug assistance could compensate.

This final use of tugs, however, takes place over a relatively small time and distance in this leg.

It was found that the pilots tended to use higher mean speeds in each leg than previously (approximately by 0.43 knot). In addition, the speed in leg 1 was slightly higher in the first leg (by 0.07 knot) and in the turn (by 0.17 knot), but the same in the final leg 3 when tugs were available. One pilot (S2), Run 4, did have difficulty entering the final leg and then overshooting the centerline. Observations of the other graphical data indicated that this was due to using insufficient right rudder late in leg 1 to initiate his turn, and insufficient correcting left rudder to enter the final leg.

Also, from the ship tracks it can be seen that as in the previous experiment, some pilots appear to use an approximately constant heading technique to cut across the turn parallel to the inner edge, whereas others used an approximately constant turn rate and followed the transition arc quite closely.

3.1.1.2 Rudder Angle, Engine RPM and Rudder Moment

Figures 3-14 to 3-19 present the time histories of rudder angle, rudder moment and engine rpm for each subject in Group 1 (S1 to S6) during consecutive runs, in the order that they appear in Table 2-2. The appropriate non-failure runs pertinent to this discussion can be readily identified by the legend. Figures 3.20 to 3.25 show similar plots but in this case also simultaneous plots of longitudinal and lateral tug forces (X_{TUG} and Y_{TUG} respectively) and tug moment (N_{TUG}). These are appropriate for subjects S7 to S12 who had two tugs in the assistance mode at all times if required.

A close examination of these plots allows one to identify the individual techniques used by the pilots to control their ship, such as at what point they anticipate turns, the frequency and magnitude of rudder used, the regulation of engine rpm to provide deceleration and/or control, etc. The use of increased propeller wash over the rudder to increase its effectiveness can be clearly seen from the simultaneous "spikes" in the engine rpm and the rudder moment (N_R). Also in the final stages in leg 3 where the engine is run at full reverse rpm in most cases to provide maximum deceleration it can be seen that rudder moment control is effectively lost. The ships are at the mercy of the wind, unless they have tugs to supply counter forces and moments.

A few selected examples of the different techniques and other observations are described below. It would be an overwhelming task to interpret and describe all these data in more detail. However, with this wealth of data available to him, the reader should be able to interpret it to any depth he desires. As an example, Subject S9 in Run 8 (Figure 3-22 (c)) employs almost textbook precision. Initially he dropped his engine speed to dead slow, and maintained this rpm until the final stages of leg 3. He then applied full right (-35°) rudder when his stem was approximately aligned with the entrance buoys 7 and 8. This he maintained for a period of about 3 minutes, where upon he returned the rudder amidships and kept it there for a further 6-1/2 minutes. He then applied hard left rudder (+35°) for about four minutes to correct the swing and enter leg 3.

To decelerate in the third leg he stopped his engine and in the final stages put it in full reverse to stop. It can be seen from the ship ground track for this run (R8) Figure 3-10 (b), that he performed very well and his final

track lay about 100 feet left of the centerline. He never found it necessary to use his available tugs. In Run 9 he displayed exactly the same technique but in this case he made use of his tugs to provide both control and deceleration in the final stages. In Run 12, he used the engines at slow ahead until exiting from the turn where he stopped them and later applied full reverse power. Possibly due to his higher engine speed, he found it necessary to make a correction during his turn using a single pulse of left rudder followed by a single pulse of right rudder. Just prior to entering leg 3 he applied the conventional correcting full right rudder. In this run he also took advantage of his tugs to provide principally deceleration and some control.

Subject S10 (especially in Run 6, Figure 3-23 (b)) demonstrated a similar technique to S9 although he did not initiate the turn with full right rudder. He also used his engines at slow ahead practically until leaving the turn whereupon he stopped them and later put them in full reverse. In this run he also did not make use of his tugs. His rudder activity was somewhat different in his final run, Run 12 (Figure 3-23 (d)), but in addition he maintained his engine speed at half-ahead until nearly the end of the turn. The amount of rudder employed in the turn is consequently smaller. His track on entering leg 3 was quite far to the right of centerline with the ship later crossing over to the left. In the final stage he used his tugs for deceleration and to a minor degree for control.

The data for Subject S2 shows that he used a different technique. In Run 4 (Figure 3-15 (a)) he set his engine at slow ahead and applied a small 10° right rudder late in leg 1, and later in the turn applied full right rudder. After entering the final leg he applied full left rudder to correct his swing for a relatively long period. His track plot indicates that he had not used sufficient rudder to initiate the turn and therefore had then to increase the turning moment in mid turn. He overshot the centerline as he did not apply sufficient left rudder correction before entering the final leg. In Run 5 he again applied a small amount of rudder but not soon enough. In this instance he applied left rudder to correct his swing in sufficient time before entering leg 3 and was able to successfully complete the transit. The same technique was indicated in Run 7. His behavior in this fourth non-failure run was very interesting -- he started to anticipate the turn very early, at buoys 5 and 6, and initially used full rudder, which he then quickly reduced to 10°. He kept his rudder amidship for over 6-1/2 minutes throughout the turn before applying left rudder and stopping his engines to enter the final leg.

Thereafter he applied clockwise and counterclockwise moments by increasing his engine rpm ("kick"), followed by final deceleration by applying maximum reverse engine power.

Subject S11 in Run 1 (Figure 3-24 (a)) was late in applying his rudder, waiting until he entered the turn. He was then forced to apply maximum right rudder, but he shut off his engine completely, thereby reducing the rudder efficiency considerably. However, he did use his engine later to increase the efficiency and generate a "kick" moment, but obviously too late. As a consequence his ship could not turn sufficiently, advanced too far and scraped the left channel bank prior to entering the third leg. On entering leg 3 he applied full left rudder to correct his clockwise swing and bring him closer to the centerline. However,

this was still insufficient and his ship overshot the centerline, but fortunately avoided a further grounding as he decelerated using full reverse engine power and luffed into the wind.

At no time did he make any attempt to use the tugs that he had to assist him, and which could have helped him in controlling the ship in the turn and in the final deceleration process.

These are but a few of the observations of the strategies used by the pilots that can be derived from a careful examination of the available plots. They indicate where some of the pilots made misjudgements and how these could have been corrected by either changing their procedures or more effectively using the tugs that were provided.

3.1.1.3 Tug Forces and Moments

As stated above, Figures 3-20 to 3-25, show the variations in the resultant longitudinal (X_{TUG}) and lateral (Y_T) forces and yaw moments (N_{TUG}) exerted by the tugs on the ship during each run. These data were obtained from the data log summary (Table 2-6) which recorded these quantities individually for each of the six selected tug positions, Figure 2-6. These data apply solely to the Group 2 subjects (S7 to S12) who had tugs in assistance which could be used at any time. In addition, the corresponding time variations in rudder angle, rudder moment and engine rpm are also presented. The runs corresponding to no failures can be identified by the legend accompanying each pilot consistent with Table 2-2. The horizontal time axis in these tug plots (and also the rudder/rpm plots) has been marked at the times corresponding to the beginning of leg 2, and the beginning of leg 3 by an arrow and the corresponding numeral. The times between the numerals 1 and 2, and 2 and 3 are indicative of the mean speed in leg 1 and in the turn. These allow a ready visual comparison to be made of the relative mean speeds in the different legs within runs and subjects.

Examination of the four non-failure runs for each Subject S7 to S12 in Group 2 clearly indicates that tugs are not generally used in the first leg or in the turn (Subject S8 in Run 5 was the only person who used tug control in the turn). In the final leg tug use was slight, and occurred with different variations in the degree of use for deceleration (longitudinal force, X_{TUG}), for control (lateral force, Y_{TUG}, and yaw moment, N_{TUG}) or combinations of both. In seven of the twenty-four runs tugs were not used at all.

3.1.1.4 Mean Track Line

The mean deviation off-track for the 250,000 DWT tanker in the absence of failures was calculated at 400 foot increments along the total transit distance. The 5100 foot radius transition arc was selected as the reference track in the 45^o turn. In Figure 3-26, the horizontal axis consists of the leg 1 (from points 1 to 2), the straightened arc length (from 2 to 3) and finally leg 3. At every 400 foot point the mean distance off-track for all tracks of the particular group of subjects (Group 1, No Tugs; Group 2, Active Tugs) at that section was determined, along with the standard deviation and the maximum and minimum values of off-track distance. This representation is very instructional since all the vital information on ship position over the whole transit is readily visible. Although the ± 400 ft. width is shown constant on these figures, it must be remembered that over section 2 to 3, the turn, the

distance between channel boundaries increases and then decreases again as shown in Figure 3-27. Hence an extreme data point in this leg 2 lying outside the 400 foot horizontal line does not necessarily mean a grounding has taken place. Such is not the case, however, in the other two legs.

Figure 3-26 shows that the mean track with and without tugs lies to the left of the designated trackline (leg centerlines and transition arc) at all times. In entering leg 3 the mean track is about midway across the left hand side of the channel. This differs from the findings of the previous experiment where the average track lay to the right of channel centerline on entering the turn, crossed over the transition arc about midway in the turn, and entered the third leg about 100 feet to the left of centerline. Hence in this case the mean centerline apears to have been moved bodily about 100 feet to the left. The mean speed of the ship was approximately 0.43 knots higher in the first leg and in the turn than in prior experiments. This group of pilots may also have preferred to stay to windward in anticipation of possible mechanical failures occurring.

With no tugs the standard deviation (consistency) in the turn and the extremes are larger than those when tugs were available, despite the fact that these tugs were not used. It was found, however, that the pilots with tugs used slightly higher mean speeds in leg 1 and in the turn, and this perhaps led to the more consistent performance.

3.1.2 Observations on Failure Runs

Failures occurred at selected points in the first leg and in the turn as shown in Figure 2-2 and according to the run order schedule of Table 2-2. They were either due to an engine failure or a rudder failure (with rudder angle of zero degrees) but not both simultaneously as in the previous experiment. These failure modes were further subdivided to allow for either no recovery or for recovery after an expected average time (five minutes for a rudder failure and ten minutes for an engine failure). On re-examining the rudder and rpm time variation corresponding to the non-failure runs discussed previously, it is apparent that rudder was generally amidship for a relatively large percentage of the time in the turn and in leg 1 and also the rpm were generally reduced to slow ahead or dead slow. Under these conditions it would seem that failures occurring in certain locations in either leg but with recovery would not present a problem. Failures without recovery however could present a serious problem, more so in the event of a rudder failure than for engine failure.

Even with a finite recovery time, the location of the rudder failure can be critical. If it should occur in leg 1 just at the point when the turn should be been initiated, then control of the ship through the turn could be difficult without tug assistance. However, if the failure occurred after the turn has been initiated and the ship has developed sufficient turn rate, the loss of rudder for a five minute period may not be serious. Should the rudder failure occur towards the end of the turn when corrective rudder is required, then again problems may be experienced in transiting the final leg without tug assistance.

A loss of engine power on the other hand will not impose such serious consequences. In legs 1 and in the turn where failure occurred the ship has moderate hull speeds (about 5 knots) at which the rudder can be used very

effectively despite the loss of the propeller wash on the rudder following failure. Hence sufficient control can be exercised by the rudder, although the ship will slow down more rapidly due to loss of thrust.

Thrust =

$$-99.4\ u^2 - 141.33\ un + 121.70\ n^2$$

(u = fps, n = rpm)

For an initial condition of 5 knots speed and 20 engine rpm (slow ahead) an engine failure would produce a change (loss) of 24,600 lb of forward longitudinal force. This can be very easily corrected for by pulling with one tug at quarter power (slow ahead). The corresponding rudder moment, N_R

$$= (-33440\ u^2 + 1241\ un - 2890\ n^2)\ \delta +$$

$$(7.443\ u^2 - 0.2761\ un + 0.6431\ n^2)\ \delta^3,$$

(where δ is the rudder angle in degrees) shows that under these same conditions (u = 5 knots, n = 20 rpm) the rudder moment N_R

$$= -3.3239 \times 10^6\ \delta + 742.08\ \delta^3$$

If $\delta = 20^o$ right rudder then N_R = + 60.541 x 10^6 lb ft. If the engine fails, $n = 0$, the rudder moment reduces to N_R

$$= -2.3877 \times 10^6\ \delta + 531.45\ \delta^3$$

$$= +\ 43.50 \times 10^6 \text{ lb ft.}$$

Consequently due to engine failure there is about a 30% loss in effective rudder moment. The maximum tug moment (= 9 PL) of 78.12 x 10^6 lb. ft could adequately compensate for this loss, if necessary. However a failure of the rudder, $\delta = 0$, would correspond to a complete 60 x 10^6 lb ft. loss in moment under these conditions and the tug moment could just about correct for this. If the rudder angle were greater than 20^o, the tugs would be inadequate in duplicating the rudder.

This discussion has not considered the added effect of the wind and the tug movements necessary to correct the failure. In some cases this wind effect may be helpful, while in others it may have a serious effect.

Similarly, if the rudder failed at an angle other than zero, this would also have a strong influence on the effectiveness of the available tug power.

The loss of engine power becomes more serious as the ship speed decreases, and at very low speeds it is the propeller wash over the rudder that provides the major contribution to the forces and moments.

During the final deceleration phase in leg 3 the engine rpm are run at full power astern (~-40 rpm). In this case where the ship speed is still forward ($u > 0$) but engine running astern ($n < 0$) the reverse thrust is approximately $X_P = -116.7\ n^2$ (assuming $u \simeq 0$) or -186,720 lb. This value is close to the maximum that could be exerted by the two 4000 BHP tugs pulling backwards at the stern of the ship (namely 27 P = 216,000 lb). Consequently the two tugs could compensate adequately for engine power loss in the deceleration mode. The clockwise yaw moment on the ship due to the reverse engine rotation (paddle wheel effect) can be represented by $N_P = 2972.2\ n^2$. With engines in full reverse power ($n = -40$), $N_P = 4.756 \times 10^6$ lb. ft. This is a small fraction of the maximum tug moment that could be exerted, (78 x 10^6 lb. ft.).

When engines are reversed and the ship is in forward motion, there is a drastic change in the rudder efficiency. This has been recognized from the rudder moments in the final phases of the various runs when compared with the corresponding amounts of rudder angle being employed (for example, see Subject 1, Run 12, Figure 3-14 (b)). The rudder moment, N_R, ($u > 0$, $n < 0$) can be written as $N_R = -18570\ u^2\ \delta + 4.134\ u^2\ \delta^3$, with no dependence on the engine rpm. Hence although the use of full power in reverse leads to a large deceleration force it does not contribute to the rudder effectiveness. Assuming a mean ship speed of 4.5 fps (about 2.7 knots) in this final leg, the rudder moment that can be obtained using maximum right rudder (-35°) is $N_R = 8.5 \times 10^6$ lb. ft. This is only about one tenth of what could be obtained using the available tug power.

3.1.2.1 Rudder Failure

As discussed in the previous section, the occurrence of a rudder failure (at zero degrees) at specific locations in the channel and/or without recovery can create a serious situation if tugs are not available to compensate for the loss of turning moment on the ship. The cases of rudder failure without recovery occurring either in the first leg or in the turn caused the pilots to take unique measures to abort their mission, when they did not have tug support. In all other cases of failures with or without tugs they continued the transit to the end.

Without tug support, once the rudder failure occurred in leg 1 the pilots immediately put their engines at full reverse power. Once they were informed that rudder had been restored, after a five minute lapse, they immediately set their engine on forward rpm and resumed conventional control. When recovery did not take place they continued at maximum deceleration with reverse engine power and stopped in the turn, where they could anchor and await assistance or repairs.

When failure occurred in the turn the same procedure was adopted. When the rudder recovered the engine was put in forward rpm and in many cases the rpm were increased in pulses (kicks) to increase rudder efficiency and consequently turning moments.

The procedure in the final stages of the third leg was again to decelerate rapidly with the engine in full reverse power. This stopping phase frequently resulted in insufficient moment and lateral forces (as discussed previously) being available to counteract the drift and luffing due to winds and currents.

When rudder failure occurred in leg 1 and tugs were available the engine was again immediately put into full reverse power and the tugs were also applied to produce a clockwise moment to swing the ship into the turn and in some cases to provide a further decelerating force. Upon rudder recovery the tugs were generally removed and the conventional control using engine rpm and rudder were resumed.

When failure occurred in the turn and tugs were available, the general tendency was not to put the engine in reverse to decelerate; in some cases the engine was stopped, in others it remained untouched. The pilots, therefore, were not attempting to slow down their ship when a rudder failure occurred in the turn. Tugs were generally applied for control and not for deceleration, and the proce-

dures paralleled those that would have been used with the rudder. They provided the lateral forces and yaw moments to counteract wind effects and on entering the third leg moments to cancel out the turn rate generated in the turn. The final deceleration was still obtained by reversing the engines. In the cases where the rudder did recover after five minutes, the general tendency was to remove the tugs and revert to conventional control using rudder and engine rpm.

Examples of pilot procedures when rudder failure occurs in the first leg with no recovery and tugs not present are shown in Figures 3-14 to 3-19 for Subjects S1 (Run 10), S2 (Run 6), S3 (Run 11), S4 (Run 9), S5 (Run 5), and S6 (Run 12). Examples of pilot procedures when the non-recoverable rudder failure occurs in the turn with no tugs can be found in these same figures for Subjects S1 (Run 1), S2 (Run 6), S3 (Run 11), S4 (Run 4), S5 (Run 7) and S6 (Run 9).

As an example of pilot procedures in using tugs following a rudder failure in the first leg we will examine Figure 3-20 (c). This corresponds to subject S7 on Run 7. It can be seen that immediately the rudder failure occurred he set his engines in full reverse and at the same time applied a maximum clockwise moment on his ship to develop his turn. This he achieved by having one tug push on the port bow at full power. He also applied his second tug at full power pulling at the stern for deceleration. He maintained this configuration until he had successfully entered the turn (about ten minutes). Thereafter he continued using his tugs intermittently and in the same manner, while he changed to forward rpm early in the turn. As a result he very slowly negotiated the turn, as can be seen by the marks indicating the beginning and end of leg 2. His final ship track can be examined in Figure 3.8 (b).

In Run 9, Figure 3-20 (c), he again experienced a rudder failure, but a little earlier in leg 1, which was corrected after a five minute delay. He used the same technique with his tugs and with his engine in full reverse. On the announcement that his rudder was again operative, he proceeded to remove his tugs and put his engine on slow ahead and later stopped. He did not use his tugs further for control, but in the final stages used them at full power in addition to reversed engine rpm to provide the maximum deceleration.

Subject S8 in Run 4, Figure 3-21 (b), used his tugs solely for control by producing a pure turning moment with his tugs at full power pushing on the port bow and the starboard quarter respectively. He maintained this configuration until about halfway around the turn, when he applied a counterclockwise moment to slow down his yaw rate and enter leg 3. In the final leg he used his tugs for both control and deceleration in the last stages.

Subject S10 in Run 1, Figure 3-23 (a), experienced some difficulty when the rudder failure occurred at the entrance to the turn. Up to that time he had not initiated his turn and consequently had to rely entirely on his tug support. Unlike the majority of the pilots under similar circumstances he stopped his engines rather than reversing them to quickly decelerate. Instead, he configured his tugs with one providing a turning moment and the other deceleration. Once in the turn he reduced the turning moment and continued using his other tug for deceleration. As a result of not using the full available turning moment (as did subject S8) for developing the

necessary yaw rate and using his second tug for deceleration rather than his engine he overshot the channel boundary as he entered leg 3.

After entering leg 3 he applied a pure counterclockwise moment (using the two tugs pushing on the starboard bow and on the port quarter) to counteract his swing and restore his track along the centerline.

In this leg he manipulated his tugs (incorrectly) so as to produce longitudinal forces that were actually tending to accelerate his ship rather than to retard it. He used full reverse engine power principally for the final deceleration stage, and his tugs for control.

In his Run 11, Figure 3-22 (d), subject S9 experienced a rudder failure after entering the turn that did not recover. He already had his engine on slow ahead and his rudder had been returned to amidship after full right rudder had been used to initiate the turn. He did not touch his engine nor did he apply any tug power to decelerate his ship. He used his tugs to produce a strong lateral force to port and a counterclockwise moment to cancel out his yaw rate in the turn, and then, in leg 3, to balance the drift and align his ship with the channel axis. On entering leg 3 he stopped his engine and later decelerated, depending entirely on reverse engine power.

Subject 11, Run 12, Figure 3-24 (d), also experienced a non-recoverable rudder failure early in the turn. He had stopped his engines almost immediately on entering leg 1, had started his turn and had returned his rudder to amidship when the failure took place. He did nothing until the time came to prepare for entering the final leg. He used his tugs to produce a relatively small clockwise moment on the ship to bring it smoothly onto the centerline, followed by a small counterclockwise moment. During this time his tugs were arranged to provide a large lateral force to port. This force resisted the tendency to drift to starboard caused by the strong beam wind. In the final stages he put his engine in reverse and used his tugs principally for conteracting force and moments due to the wind.

These are just a few examples of the insight into piloting techniques that can be derived from closely observing the simultaneous data on ship tracks, tug force and moments, rudder and engine rpm.

In summary, therefore, in the event of a rudder failure and without tug assistance, and whether the failure occurs in the first leg or in the turn, the procedure is to immediately brake by putting engine in full reverse and keeping it there until the failure is corrected or the ship has stopped.

With tug support and the failure occurring prior to the turn, the procedure is:

1) To decelerate immediately by putting the engine in full reverse,

2) At the same time use the tugs to provide the necessary yaw moment to initiate the turn (and further deceleration if desired), and then essentially to duplicate the rudder control processes that have been lost and

3) Use the tugs for the final deceleration, where it has been found that tug assistance is advantageous at all times for the 250,000 DWT tanker.

However, if the turn has already been initiated when the failure occurs there

is no attempt to decelerate further by using the engine, which is not touched.

Tugs are used to compensate for the loss of rudder by providing correcting yaw moments and lateral forces to balance the wind drift and prevent luffing.

3.1.2.2 Engine Failure

As mentioned previously in Section 3.1.2 it was not expected to find the pilots experiencing difficulties due to engine failures, whether of finite duration or not. Generally under normal conditions the engine rpm are at a low level or even zero for a major part of the transit. As demonstrated in the simple calculations in Section 3.1.2, a loss of engine power does not significantly reduce the rudder efficiency at the ship speeds encountered in the first leg or in the turn. The amount of thrust that is lost is also not a significant quantity and can be very easily compensated for by using tugs if available. If tugs are not available then the ship will slow down more quickly. Consequently the rudder effectiveness will reduce and larger rudder angles will be required for control.

On examining the ship tracks (Figures 3-2 to 3-13) and the corresponding tug and rudder data (Figures 3-14 to 3-25), it is obvious that the above is indeed true. Effective control is carried out conventionally using the rudder. When tugs are present they are used primarily for deceleration, although they can also supplement the rudder moments. In the final stages they are effectively used for both deceleration and control.

In this final deceleration phase the ship is totally dependent on the availability of the tugs. This function was carried out primarily by the engine under normal no-failure and rudder failure conditions.

As a result of the specific techniques employed with rudder and engine failures the mean speeds in the turn and in the final leg for each condition were different. The mean speed in leg 3 and in the turn was greater when an engine failure occurred, independent of the location of the failure, when there were no tugs. With tug support, the mean speed in leg 3 and in the turn was again greater in the case of an engine failure when the failure occurred in the first leg. When the failure occurred in the turn, the mean speed in the third leg was greater for a rudder failure than for an engine failure. (See Table B-40.) However, these observations are greatly influenced by the contribution of the no recovery rudder failure in both leg 1 and in the turn, where the ship stops in the turn or early in Leg 3.

3.1.2.3 Mean Tracks for Failure Runs

The mean tracks and the corresponding standard deviations and extremes for the cases of rudder failures (RA and RI) and engine failures (EA and EI) were determined at 400 feet intervals. Figure 3-28 (a) presents these data graphically for rudder failures occurring in the first leg with two active tugs and no tugs respectively. Figure 3-28 (b) shows similar plots for the case of engine failures in leg 1. The plot for the case of rudder failure with no recovery was terminated at the entrance to the turn when no tugs were available. Under this failure condition, the pilots came to a stop soon after entering the turn.

It can be observed that when rudder failures occurred in the first leg and tug assistance was available the mean track lies to the left of the designated track, the distance increasing uniformly with distance travelled in the turn, and enters the final leg at about

midway on the left side of the channel (≈200 feet). Without tugs however the mean track lies even further to the left (≈300 feet) as the ship enters the final leg.

In the case of an engine failure in leg 1, the mean tracks in the turn and in the final leg still lie to the left of the designated track, generally about 150 feet. The distance between the mean track and the transition arc in the turn increases steadily with distance along the arc. The standard deviations are smallest with tugs and no recovery, but large when recovery took place, similar to when no tugs were present. Hence the most consistent performance among the pilots occurred when engines failed and did not recover, but tugs were assisting. Also in this case, the mean track lay to the right of the centerline on entering the turn, then crossed over the transition arc about half way around the turn, and then entered the final leg about 150 feet to the left of centerline, and continued with this offset until the end of the transit.

Figures 3-29 (a) and 3-29 (b) present similar data for the cases where failure occurred in the turn. Again for rudder failure without recovery and no tugs the plot has been truncated at the entrance to the third leg, due to the unique strategy in this case. The mean track again diverges uniformly from the transition arc in the turn and enters the third leg approximately midway on the left side. The standard deviations are significantly smaller when tugs are assisting, indicating a much more uniform performance among the pilots. With engine failures similar consistency was observed with tugs and recovery, although the mean track is still 200 feet from the centerline at the entrance to leg 3, but was reduced to 100 feet at the end. Without tugs the mean track in leg 3 was approximately 100 feet to the left throughout. The standard deviations and the extremes were largest in the case of no tugs and no recovery, although the mean track never exceeded 200 feet to the left of the designated track, and did decrease steadily to zero in the third leg.

In summary, the general tendency of the mean track throughout was to keep to the left of the transition arc in the turn. The distance between the mean track and the curve increased approximately linearly with distance travelled along the arc.

The mean track entered the third leg about midway on the left side of the channel, and generally terminated at about 100 feet to the left of centerline.

3.2 STATISTICAL ANALYSES

The previous discussion in Section 3.1 was based purely on qualitative observations and correlations of simultaneous plots of ships' tracks and the corresponding controls (rudder, engine speed and tugs) that were used. The following sections of this report will consider the quantitative implications derived from statistical analyses of the performance measures discussed in Section 2.12. These statistical analyses were based on Analysis of Variance procedures (Anova) on the experimental data, supplemented by Neuman-Keuls multiple comparison procedures. Table 2-7 shows the Anova Source Table that gives the significant dependencies of the selected performance measures on the various factors (main effects) and their interactions to significance levels of 0.001, 0.01, and 0.05.

This discussion will attempt to summarize the main conclusions that can be drawn from these comparative analyses. Not all the performance measures treated in the analyses will be discussed in detail.

As discussed in the previous sections, the procedures used in the event of a rudder failure without tugs and no recovery were unique. The pilots immediately used their engine in full reverse to come to a stop as soon as possible. As a result, when the failure occurred in the first leg they stopped about midway through the turn. When it occurred early or midway in the turn they stopped either toward the end of the turn or very early in the third leg. If the failure occurred late in the turn they stopped about halfway along leg 3. As a consequence, there is generally no data or little data on ship speed and swept path for leg 3, that can be automatically fed into the data matrix for the ANOVA. To compensate for this missing data, it was considered reasonable to have zero speed in leg 3. For swept path, it was made identical to the average for the non-failure runs (239 feet). Obviously zero swept path is unrealistic, since it should at least be the beam width (170 feet). The 69 foot difference would correspond to an average drift angle of about 3-1/2^{o}.

The rudder angle and therefore the time rudder is used are both zero in leg 3, since failure without recovery has taken place either in leg 1 or leg 2.

The main effects results which encompass the various run combinations therefore reflect the influence of this unique case. The comparative analyses in Appendix B however allow this special case to be isolated from the others if required.

3.2.1 Mean Speed

Table B-1 (main effect, C) indicates that there is no significant difference between the overall mean speed with or without tugs (about 3.93 knots). However, there is a significant different in the case of main effect E (Table B-2) with a larger mean speed in the case of engine failure. The mean speed decreases significantly between cases of no-failure and finite recovery (in 5 minutes for the rudder and 10 minutes for engine failure). However, the difference is insignificant between finite recovery and no recovery (Table B-3, main effect T). There is also a significant effect of the location of the failures, the speed being significantly higher (about 0.3 knot) when failure occurred in the turn (Table B-4, main effect P). Finally, there is a very significant variation in mean speed between legs, the mean speed decreasing from 5.56 knots in leg 1, 3.83 knots in the turn, to 2.34 knots in the final leg (Table B-5, main effect, L). It must be remembered that these mean speeds, especially in the third leg, reflect to varying degrees the unique character of the runs involving rudder failure with no recovery and in absence of tugs. More details of this influence are provided by examining the significant interactions as listed in Table 2.7. These are presented in the Appendix B in Tables B-38 to B-40.

In the event of no failures (corresponding to the combination of E_1 T_1 and E_2 T_2 at both P_1 and P_2 in Table B-39), the mean speeds in each leg can be found. These are listed in Table 3-1.

This table shows that the mean speed in each leg and overall is greater than that found in the previous experiment (McIlroy, 1982) also using the 250,000 DWT tanker with and without 2 tugs of a total 8000 BHP. The mean differ-

TABLE 3-1. COMPARISON FOR MEAN SPEEDS IN EACH LEG BETWEEN PRESENT AND PREVIOUS EXPERIMENTS

	Leg 1	Turn	Leg 3	Average Over Legs
This Experiment (Mean Speed)	9.53	7.27	4.54	(7.12)
Previous Experiment (Mean Speed)	8.88	6.37	3.90	(6.38)
Difference in Speeds	0.65	0.90	0.64	(0.74)
	(0.39 kts)	(0.53 kts)	(0.38 kts)	(0.44 kts)

ence is about 0.44 knot. This higher speed (which increases the rudder effectiveness and also reduces the influence of the wind) leads to a much smaller rudder contribution (Section 3.2). There is a decrease in the percentage of time right rudder is used *but an increase in the percentage of* time left corrective rudder is used, particularly in the final phases (Section 3.2.8).

Table B-39 (interaction ETPL) indicates that the mean speed is significantly different in each leg for each combination of system failure and recovery time. There are significantly higher speeds in the final leg after an engine or rudder failure occurs in the turn. In the third leg the mean speeds are significantly lower in the case of the rudder failure with no recovery, which has been discussed earlier. The speed is lowest when failure occurred in the initial leg, and these results again reflect the influence of the singular behavior in the absence of tug support. Table B-40 (interaction CEPL) shows again that the mean speeds in each leg decrease significantly going from leg 1 to leg 3, over all the possible recovery times (T1, T2, T3). The difference due to position of failure is again apparent, especially in the second leg. The mean speed is always greater when failure, either engine or rudder, occurs in the turn, with or without tug support. *In the event of* a rudder failure with tug support the mean speed in leg 3 is significantly greater when failure occurs in the turn than when it takes place in the first leg.

The lowest values of speed are seen to occur again in the third leg and for the case of no tugs and rudder failure. This is a result of the strong influence of the behavior when no recovery takes place.

3.2.2 Swept Path

Table B-16 (interaction CTL) indicates that there is a significant increase in swept path between legs except in the case of no recovery. The swept path in the turn is generally much larger than that in the first leg but decreases in the third leg. When there is no recovery the swept path in legs 2 and 3 are not significantly different

whether tugs are available or not. Table B-17 (interaction ETL), on the other hand, shows how the swept path depends on the actual system effected. There is no significant difference between the values of swept path except in the third leg and no recovery. Here again the rudder failure/no recovery combination accounts for the difference.

3.2.3 Distance Off-Track Contribution

The distance off-track contribution to the performance index is $(Y_{RMS}/100)^2$ where Y_{RMS} is the conventional RMS deviation off-track measure. Consequently if Y_{RMS} is required, it can be simply found from

$$Y_{RMS} = 100\sqrt{\text{Distance Off-Track Contribution.}}$$

Table B-31 (interaction TL) indicates that this contribution is greatest in the turn, next largest in the final leg, and quite low in the first leg in the no failure condition. There is a significant increase in the third leg when the recovery time is increased. For the average recovery time the value of the off-track deviation is smaller in the turn (but not statistically significant) than for no failure and for no recovery. However, the value in the final leg does not change significantly from its value in the turn.

Translating these contributions into actual RMS deviations, the maximum value in the turn is 133 feet and 101 feet in the final leg for the case of no recovery.

3.2.4 Rudder Contribution

Table B-33 (interaction EPL) clearly shows the increased rudder contribution when an engine failure occurs. When an engine failure takes place in the first leg, significantly more rudder is used to compensate than when failure occurs later. This would be expected. In the turn the difference due to position of failure is not significant. However in the final leg where deceleration is usually performed using the engine, more rudder and tug power are used for deceleration and control; more so when the failure occurs later in the turn. Failure of the rudder automatically leads to a reduction in the rudder contribution and this is considerable when no recovery occurs. Consequently although the rudder contribution in this case differs significantly between leg 1 and the turn, the only significant difference with position appears in the first leg when failure occurs in the turn. As would be expected the rudder contribution is much less when rudder failure occurs in the first leg.

Table B-34 (interaction TPL) shows that significant differences occur due to failure position. When failures occur in the initial leg there are significant differences between rudder contributions in leg 2 and leg 3. There is no significant difference in rudder contribution between the case of no failure and of average recovery time in any leg. However, when failure occurs in the turn the significant difference occurs only in the final leg as would be expected.

The maximum rudder contribution occurs in the final leg (0.481 for failure in leg 1 and 0.569 for failure in the turn) for failures with recovery. These correspond to RMS rudder angles of 24° and 26° respectively.

The decrease in rudder contribution in the final leg when no recovery takes place is due to the loss of rudder for an extensive time period. In the

engine failure case extra rudder was used to compensate as can be seen in Table B-33.

The interaction CETL, Table B-35, clearly shows the differences in rudder contribution between engine and rudder failures. Without tugs, and an engine failure values significantly higher than under the non-failure condition occur in leg 2, and increase with failure time. In leg 3 the difference in rudder contribution between no failure and average failure conditions is insignificant, but changes significantly when there is no recovery. With tug support, however, the only significant difference with failure time occurs in the third leg. The rudder contribution increases significantly for the average failure time and there was no further significant increase with extended failure time.

With rudder failure and no tug support there is a significant effect of failure time in leg 2. Although there is a non-significant change in leg 3 between no failure and average failure, both are significantly different from the case of no recovery. This is due to the fact that the rudder is completely lost in this leg. The same is true when tugs are present.

The presence of tugs results in a decreased use of rudder in leg 2 for all time of failure conditions, and also in the final leg only for the no recovery condition. For the rudder case, there is significantly more contribution in the turn when tugs are not present and there is no failure, and also in the third leg when recovery takes place.

3.2.5 Tug Contribution

The tug moment contribution $(N_{TUG}/N_{MAX})^2$ can be examined in Table B-37 which considers the interaction ETPL. This shows principally non-significant variations with combinations of failures and recovery times. However, there are significant variations in the case of a rudder failure with no recovery.

When failure occurs in the first leg there are significant differences in tug contribution between legs 1 and 2 and between 2 and 3. The highest value (.515) occurs in the turn and the values in the first leg and third leg are not statistically significantly different. This clearly demonstrates the effective use of the tugs for control in the turn (N_{RMS} = 0.72 times maximum possible tug moment), and less in the third leg where they are principally used for deceleration rather than control. The E (system) comparison indicates that significant differences occur in legs 2 and 3 only for the no recovery condition and failure in the first leg; the greater contribution being of course with the rudder failure.

3.2.6 Inherent Risk Factor, α_2

The inherent risk factor shows no significant effects for recovery time and failure position in the event of an engine failure, whether tugs are present or not. Such is not the case when a rudder failure occurs. Without tugs and rudder failure in the first leg there is a significant decrease in α_2 between no failure and average recovery conditions but no significant change as recovery time is increased. When the failure occurs in the turn the inherent risk does not change with failure time. The position of failure does not have any effect on the inherent risk for engine failures with and without tug assistance, or rudder failures without tugs, independent of the length of time the failure lasts. The case of a rudder failure and with

tug support is quite different. Here the position of failure is important -- the risk is greater when failure occurs in the turn. Also there is a significant decrease in risk as the failure time is increased, due to the presence of tugs for control.

Table B-26 illustrates the variation of inherent risk, α_2, between legs. There is a significant difference in all cases. The highest risk occurs in the turn, the next highest in the first leg and the lowest value in the final leg. This is obviously due to the restricted maneuvering area available in this scenario.

With an engine failure and no tugs assisting (C1 E1) there is a (statistically) significant decrease in α_2 in leg 1 between average failure and no failure, and then an increase again with increased failure time. In the other two legs the variation with recovery time is not significant. With tugs available again there is no significant dependence on recovery time.

In the case of a rudder failure without tug support there is also a slight (but significant) drop in α_2 in the turn when an average failure occurs.

However, when tugs are present there is a significant decrease in risk in the turn from 0.914 to 0.674 as failure time is increased. In the other two legs the changes in α_2 are not significant.

Table B-27 (interaction CEPL, Comparison E) also shows that the only significant effect of failed system (E) occurs in the turn and in the case with tug assistance and failure in the first leg. In this instance the risk is larger with the engine failure than with the rudder failure. Also, in this particular case (C2 E2) there is a significant increase in risk in the turn when the rudder failure occurs in the turn.

3.2.7 Combined Performance Measure, J2

The main effects of tug mode (C), time of recovery (T), and location of failure (P) do not produce any significant variation in J2. However, there is a variation depending on the system failed (E). Table B-2 indicates that higher values of J2 are produced by engine failures than by rudder failures. The major contributors to this difference are larger off-track deviation and rudder contributions in the case of engine failures. The inherent risks are essentially identical for the two systems.

Table B-21 (interaction TL) shows practically no significant dependence on the time duration of the failure, except in the turn. Here the value of J2 is significantly smaller under the average failure time condition than the equivalent values for no failure and no recovery (both of which are not significantly different). The highest value of J2 always occurs in the turn, principally due to distance off-track and rudder contributions. Table B-21 indicates that for the cases of no failure and an average failure the values of J2 are not significantly different between the initial and final legs. When there is no recovery, however, the J2 values in all three legs are different. The highest value occurs in the turn and the lowest in the first leg. The only difference due to failure occurs in the turn. The influence of the position of failure can be found by examining Table B-22 (interaction, CEPL). These data indicate no difference in any leg due to failure position for an engine failure and with tug support. For a rudder failure, on the other hand, and with tugs available the value of J2 is larger in the turn when failure occurs in leg 1 than when it occurs in the turn.

The values of this combined performance measure in all cases are largest in the turn and lowest in the first leg. When there are no tugs available and a rudder failure takes place, J2 does not depend on failure position. For an engine failure and no tug support, J2 is greater in the turn when failure occurs in leg 1, but greater in the final leg when failure occurs in the turn. The comparison (C) indicates that this performance measure is greater in the turn for an engine failure occurring in either leg 1 or the turn in the absence of tug assistance.

Similarly in the case of a rudder failure J2 is greater in the turn when tugs are absent and failure occurs in the turn. Also, it is greater in the final leg when failure takes place in the first leg but with tugs assisting.

3.2.8 Percentage Time Left/Right Rudder

In the non-failure runs (T_1) the percentage of time right rudder is used can be derived from Table B-8 by combining E_1 T_1 and E_2 T_1. As a result the values in Table 3-2 were obtained. The corresponding values derived from the previous experiment (McIlroy, 1982) are also listed.

This table shows that the percentage time that right rudder is used was much higher in all legs in the prior experiment than in this experiment. The smaller rudder use may be attributed to the higher mean speeds of the ships in this experiment (Section 3.2.1). In addition, a further factor may be the influence of the bank moments on the ship. In this experiment the mean track of the ships lies to the left of track, especially in the third leg and consequently the ship experiences suction forces and clockwise moments from the interaction with the left bank. These moments are counteracted by the application of left rudder. The bank interaction moment opposes the wind moment and consequently reduces the need for corrections using right rudder. Hence the amount of right rudder should be expected to decrease, whereas the amount of left rudder should increase. The largest difference is indeed found to occur in the final leg. The percentage of time left rudder is used is obtained from Table B-6 and is compared with the corresponding values from the previous experiment in Table 3-3.

This comparison shows that the percentage time left rudder is used does indeed increase in this experiment and very significantly in the final leg.

In the case of engine failures, Table B-6 indicates that for all failure times, including non-failure, there is a significant increase in percentage time left rudder is used between the first leg and the turn but no further significant increase in the final leg.

TABLE 3-2. COMPARISONS OF PERCENTAGE TIME RIGHT RUDDER

	Leg 1	Leg 2	Leg 3	Average
This Experiment	40.9	40.9	30.4	(37.4)
Previous Experiment	62.0	54.6	51.6	(55.4)

TABLE 3-3. COMPARISON OF PERCENTAGE TIME LEFT RUDDER

	L_1	L_2	L_3	Average
This Experiment	5.3	26.4	31.3	(21.0)
Previous Experiment	4.6	18.2	10.3	(11.0)

The comparison for failure times shows that the only significant effect occurs in the final leg. Although the value decreases in this leg for the average failure condition, the value with no recovery is comparable to that when no failure occurs.

For the percentage time right rudder (Table B-8) the only significant effects that depend on channel legs occur when failure takes place with recovery. The values in the first and third legs are then comparable, and the value in the turn is smaller. In the final leg there is also a significant effect of failure time. There is a significant increase between the cases of no failure and average failure time, but the value does not change significantly as the failure time increases.

The location of the position of engine failure only effects the time of left rudder and then only in the third leg, where left rudder is used more when failure occurs in the turn.

With rudder failures, Table B-6, there are significant decreases with recovery time in the use of left rudder in the turn and in the final leg. In the case of no recovery the value in the third leg is naturally zero. There is a significant increase in the value with leg for the no failure and average failure cases. In Tables B-6 and B-8 the significant differences in time of left and right rudder that are encountered are merely consequences of both the length of time and position of the failure. The non-failure cases have already been discussed.

3.2.9 Mean Longitudinal Tug Force, $\overline{X}_T$

Table B-41 shows that the mean tug force $\overline{X}_T$ responsible for producing deceleration increases significantly throughout the transit, whether failures take place in the initial leg or in the turn. This retarding force is largest in leg 1 when failure occurs in leg 1, and largest in leg 3 when failure occurs in the turn. In the turn itself the force is essentially independent of the failure location.

Table B-42 (interaction CETL) clearly shows a significant increase in $\overline{X}_T$ in the case of an engine failure, especially in the final leg. This concurs with the qualitative discussion in Section 3.1. The value of $\overline{X}_T$ in the third leg increase rapidly as the failure time increases. However, there is no significant difference between the values in the first leg and in the turn.

In the case of a rudder failure, where engine power is still available for deceleration, the tugs are used mainly to compensate for the loss of rudder moment rather than deceleration over the major part of the transit.

As a consequence, the value of the decelerating force does not change

significantly in the final (deceleration) leg with the time duration of the failure as it does in the case of an engine failure.

In the E (system) comparison it can be seen that the mean tug decelerating force in the turn for an average failure time is significantly greater in the event of an engine failure (0.055) than it is with a rudder failure (0.009). In the final leg $\bar{X}_T$ is greatest for the engine failure independent of whether recovery takes place or not.

3.2.10 Mean Lateral Tug Force, $\bar{Y}_T$

Table B-2 (main effect, E) indicates a significantly larger $\bar{Y}_T$ (the lateral tug force that contributes to the turning moment of the ship and to counteracting drift) for the case of rudder failures than for engine failures. Again, this can be related to the fact that when an engine failure occurs tugs are used principally to produce deceleration, and when a rudder failure to produce moments. Table B-3 indicates a significant increase in $\bar{Y}_T$ with increased failure time, but no differences related to failure position. Table B-5 also indicates an increase in $\bar{Y}_T$ with leg, with the maximum value occurring in the third leg. Table B-43 shows a significant increase in $\bar{Y}_T$ when failure occurs in the first leg rather than in the turn. There is a significant increase with leg, the maximum being in the third leg (Table B-44). $\bar{Y}_T$ is greater in Leg 1 and in the turn with a failure in the first leg, but greater in leg 3 when failure takes place in the turn.

Table B-45, comparison E, shows that the lateral force $\bar{Y}_T$ is greatest in all legs for rudder failures with no recovery (E_2 T_3), and also in leg 3 for an average recovery time (E_2 T_2). In all other combinations of leg and duration of failure there are no significant differences between the values of $\bar{Y}_T$ for engine and rudder failures.

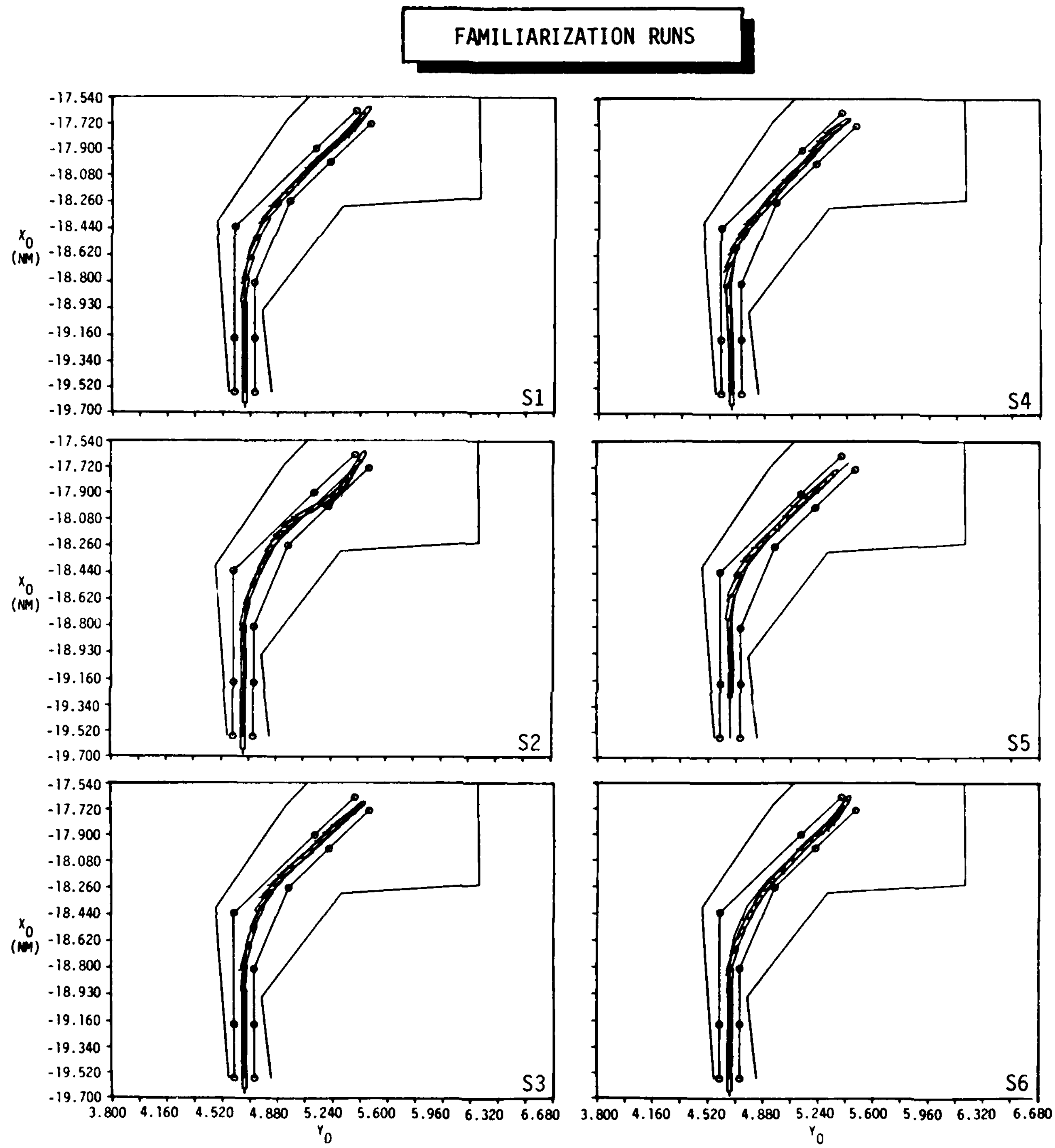


Figure 3-1 (a). Familiarization Run Ground Tracks (S1 to S6)

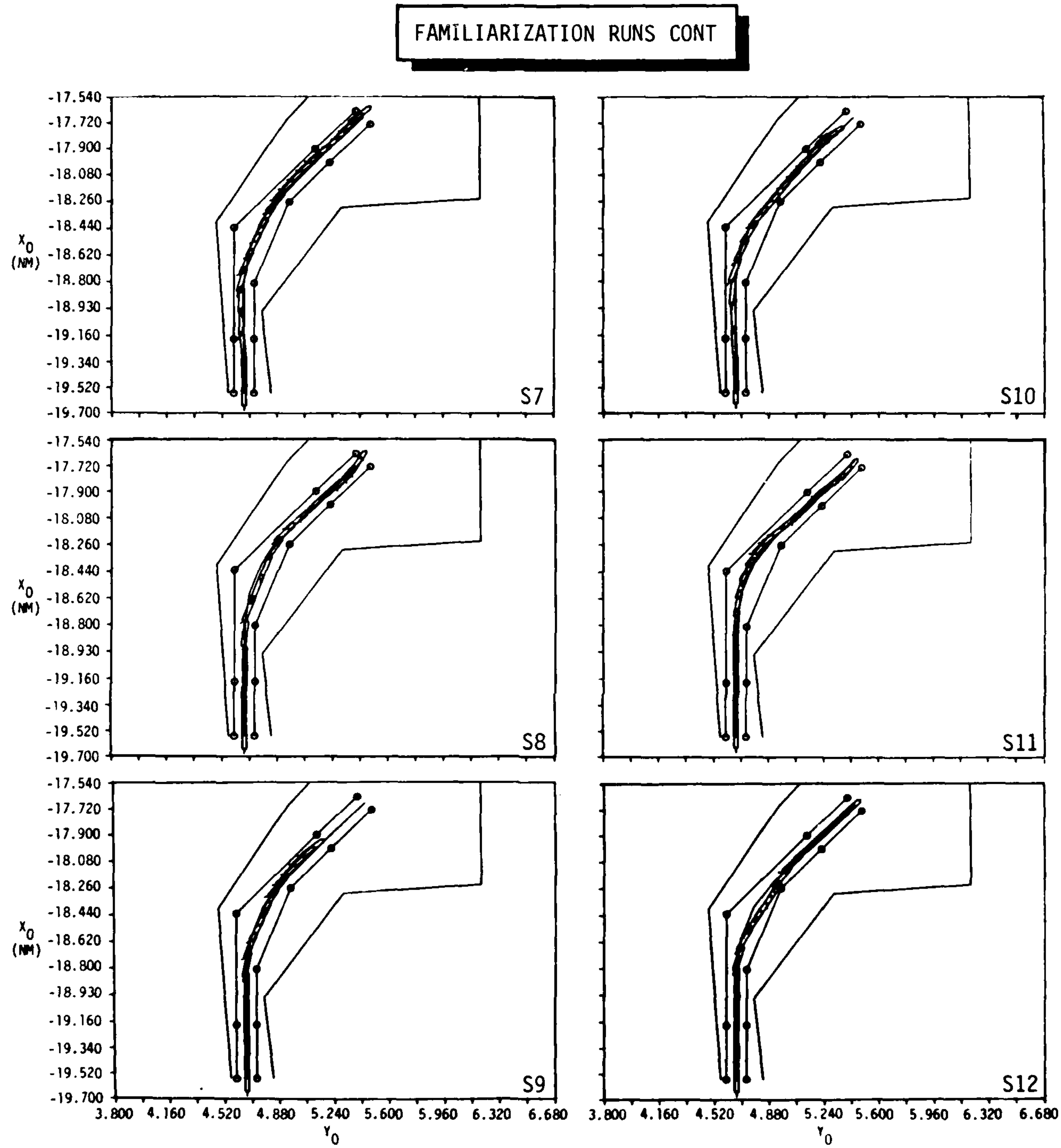


Figure 3-1 (b). Familiarization Run Ground Track (S7 to S12)

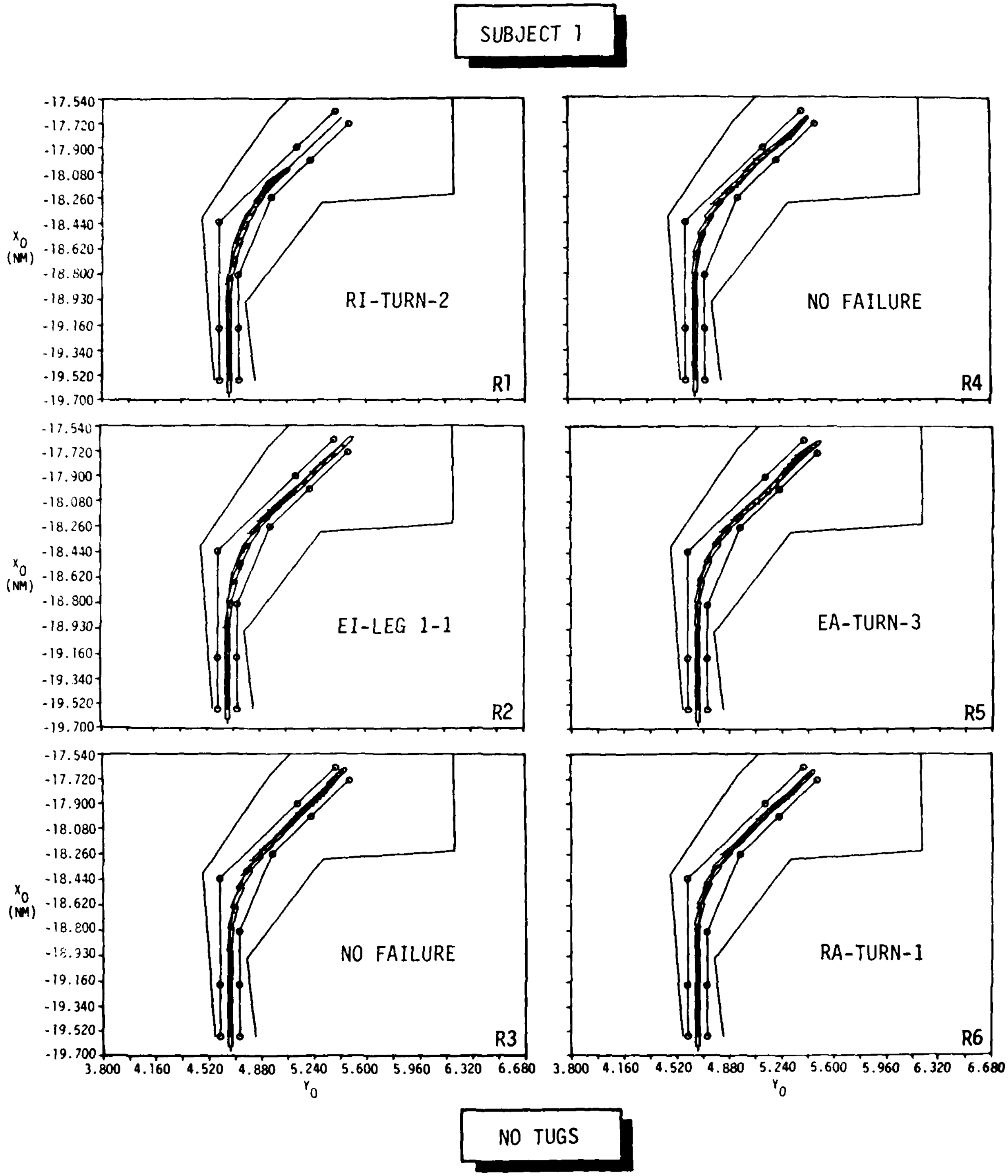
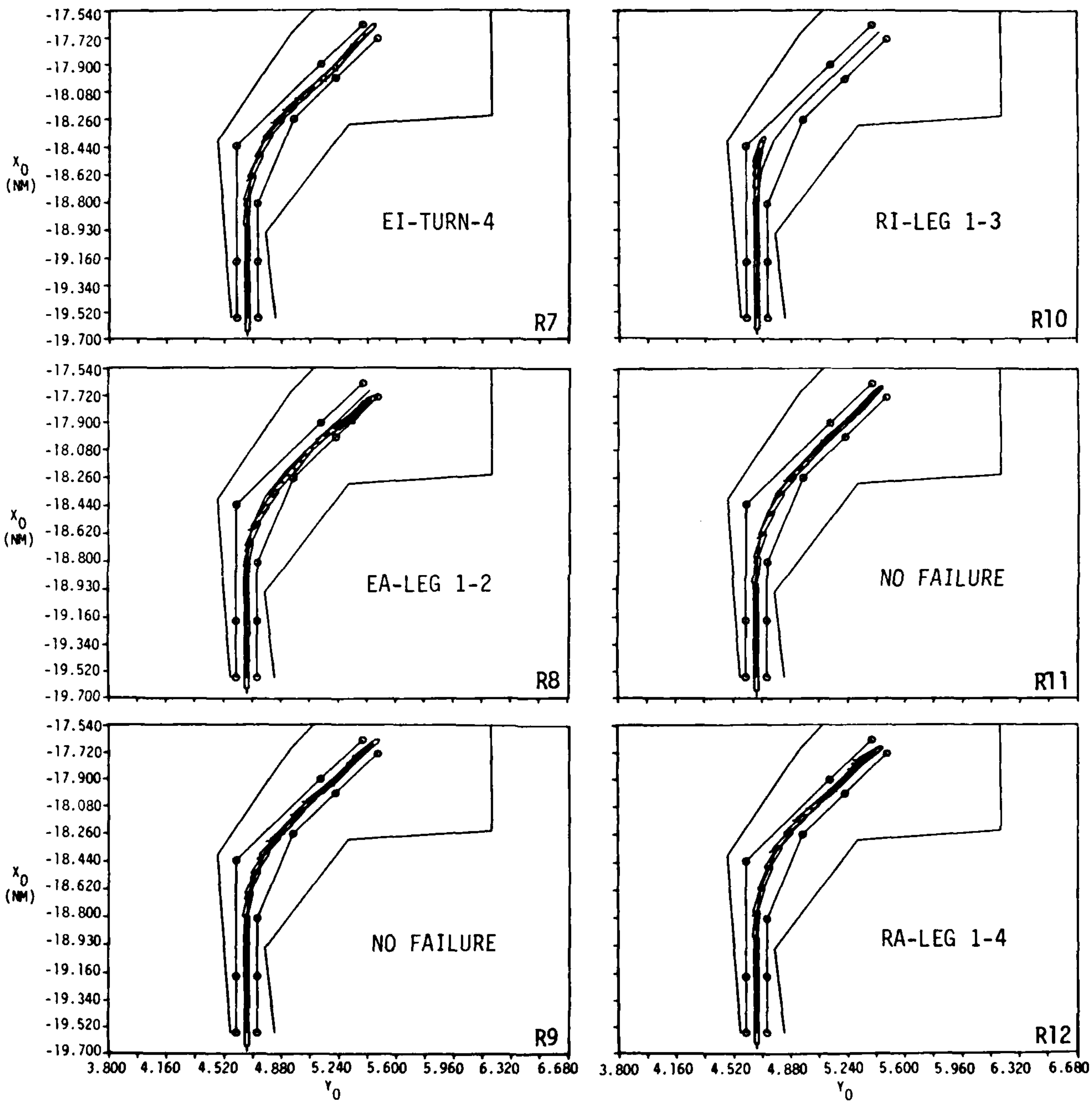


Figure 3-2 (a). Ground Tracks for Subject 1, No Tugs, Runs R1 to R6

SUBJECT 1 CONT



NO TUGS

Figure 3-2 (b). Ground Tracks for Subject 1 (Cont), No Tugs, Runs R7 to R12

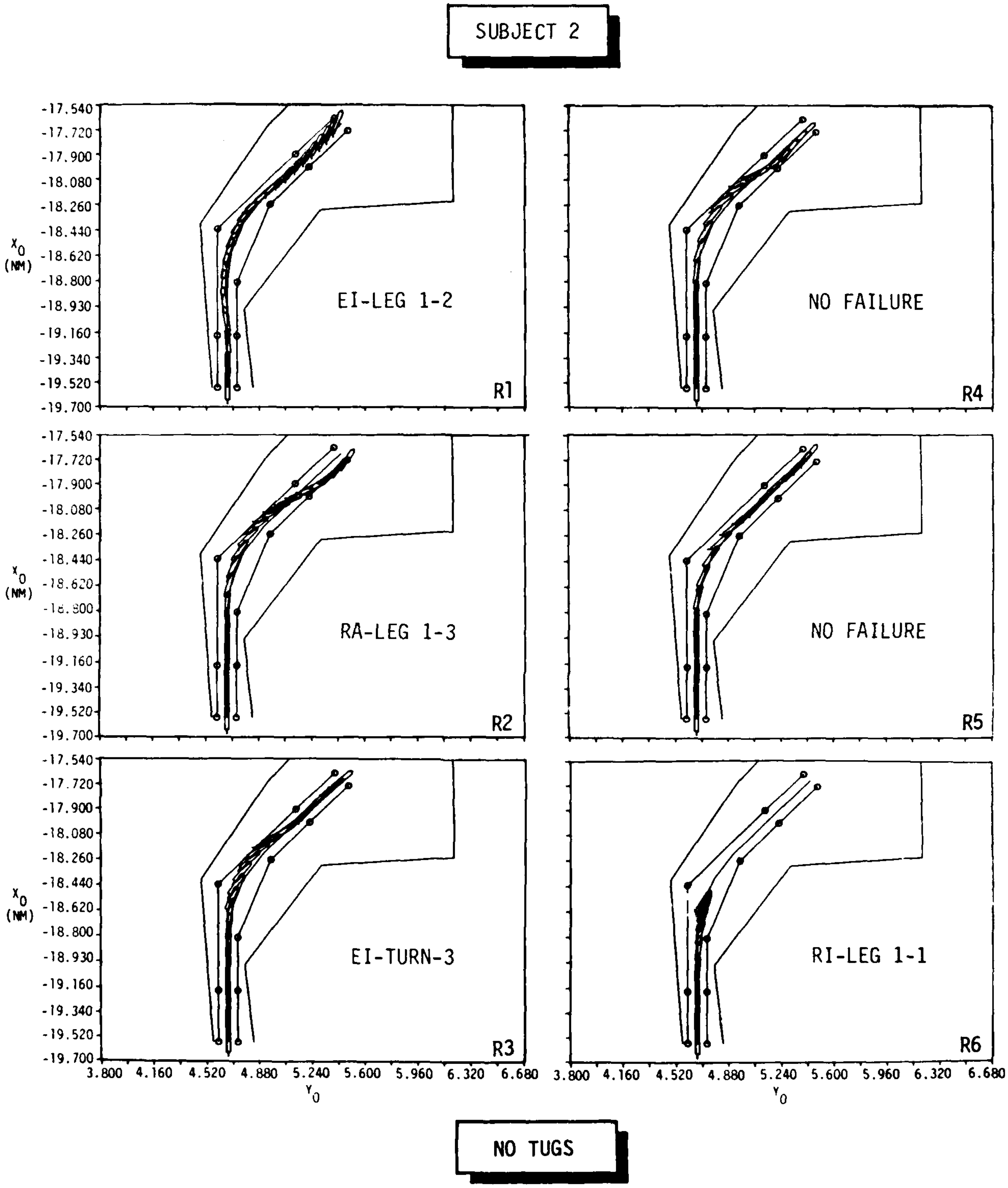


Figure 3-3 (a). Ground Tracks for Subject 2, No Tugs, Runs R1 to R6

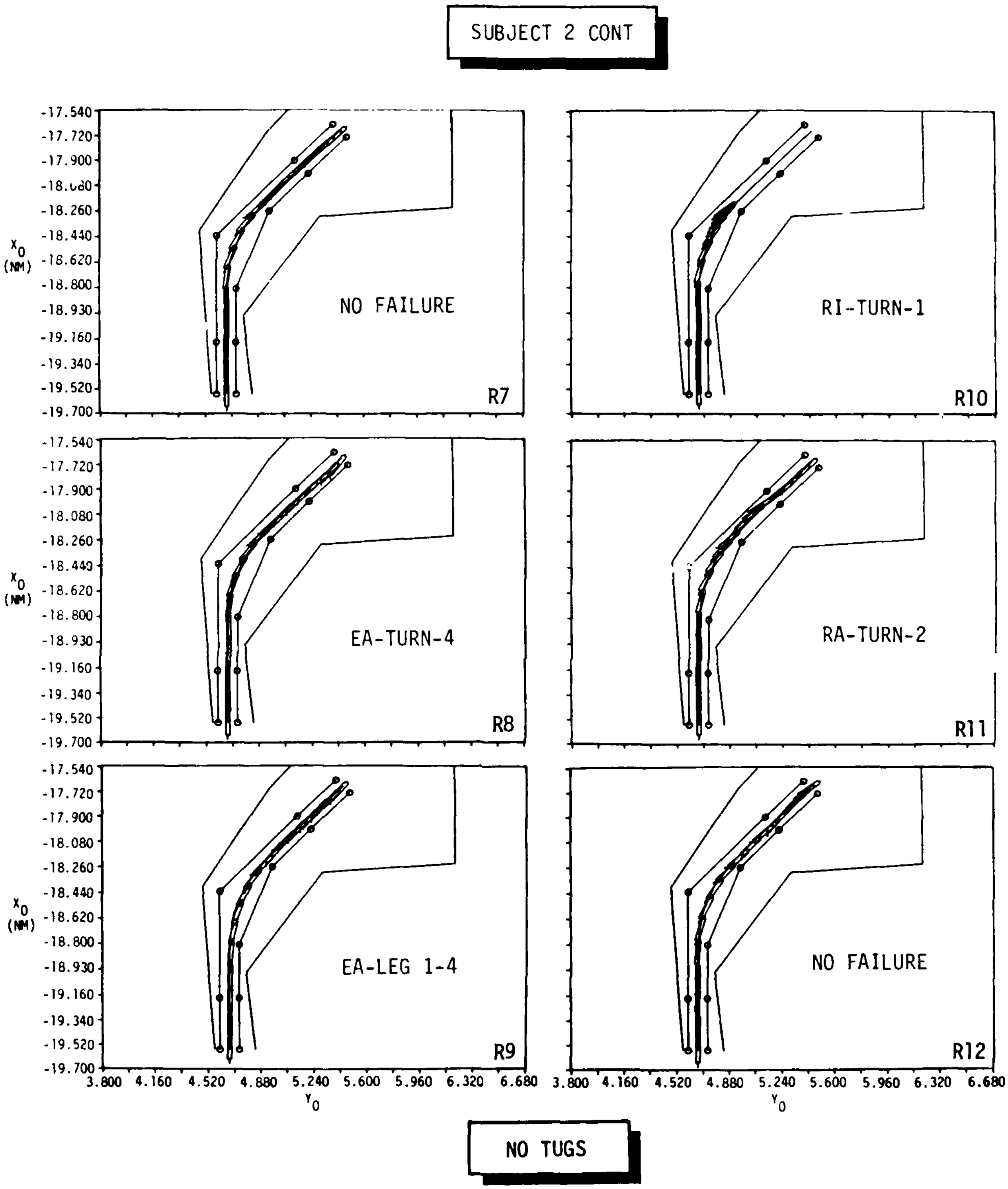


Figure 3-3 (b). Ground Tracks for Subject 2 (Cont), No Tugs, Runs R7 to R12

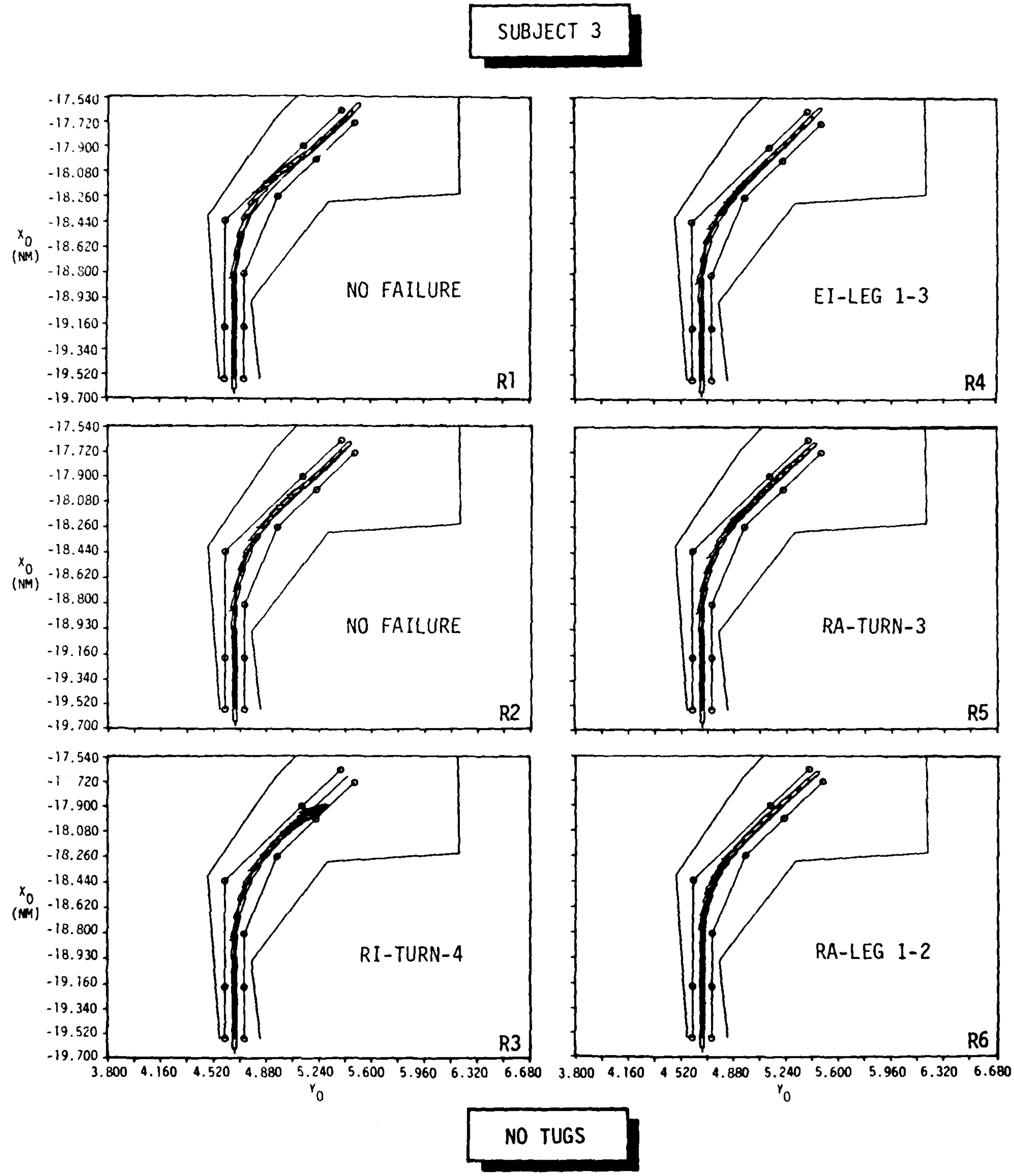


Figure 3-4 (a). Ground Tracks for Subject 3, No Tugs, Runs R1 to R6

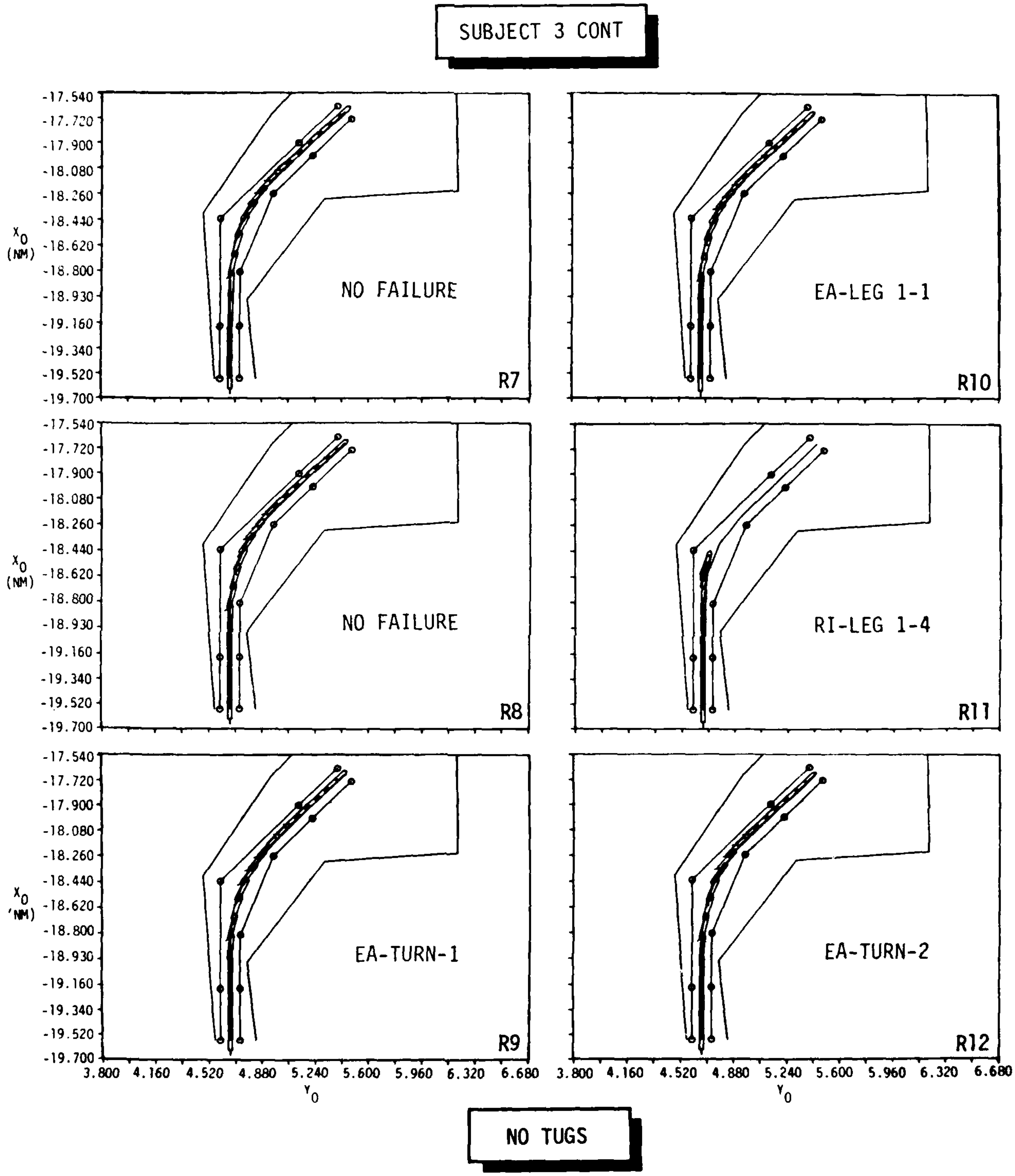


Figure 3-4 (b). Ground Tracks for Subject 3 (Cont), No Tugs, Runs R7 to R12

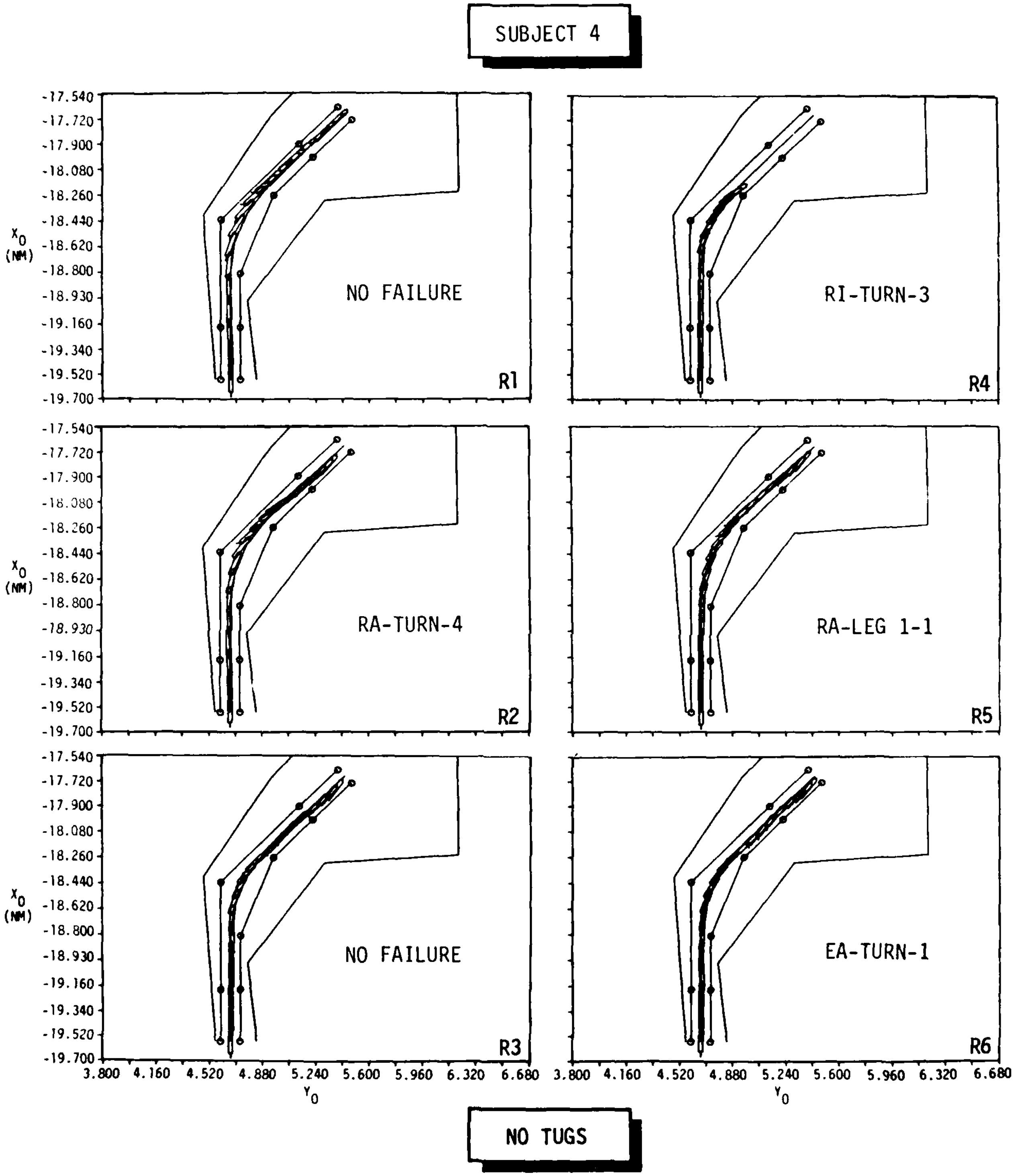
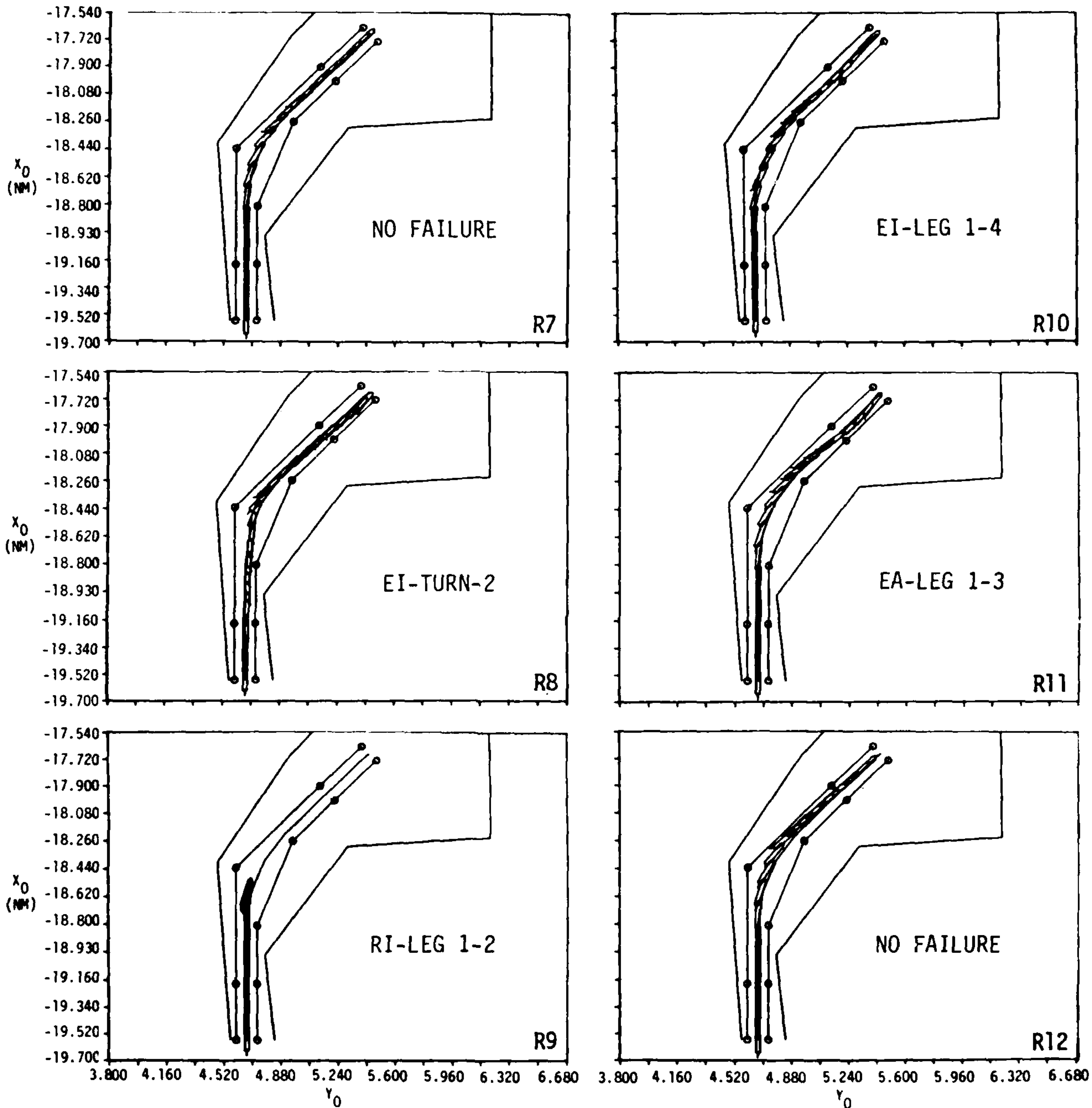


Figure 3-5 (a). Ground Tracks for Subject 4, No Tugs, Runs R1 to R6

SUBJECT 4 CONT



NO TUGS

Figure 3-5 (b). Ground Tracks for Subject 4 (Cont), No Tugs, Run R7 to R12

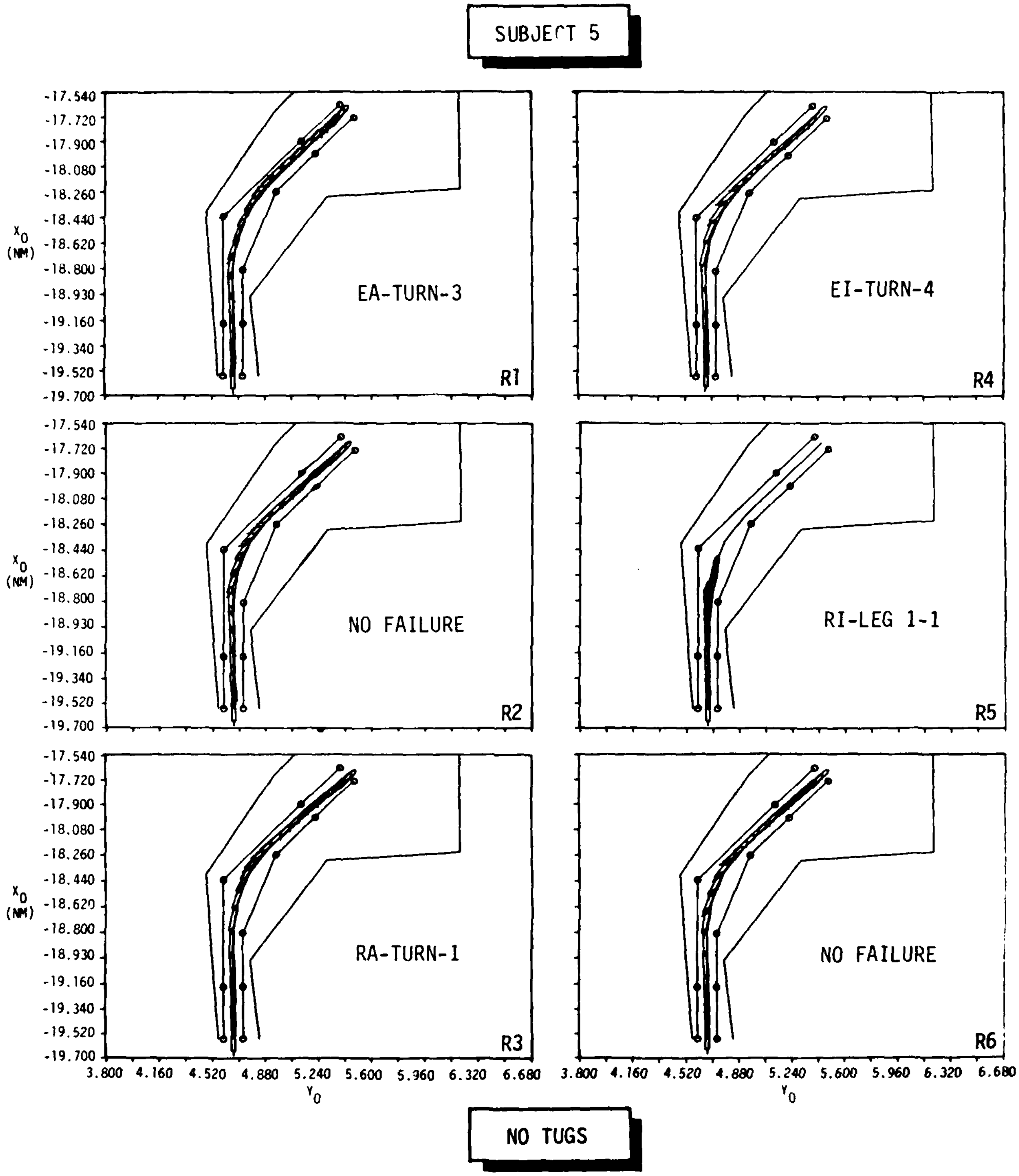


Figure 3-6 (a). Ground Tracks for Subject 5, No Tugs, Runs R1 to R6

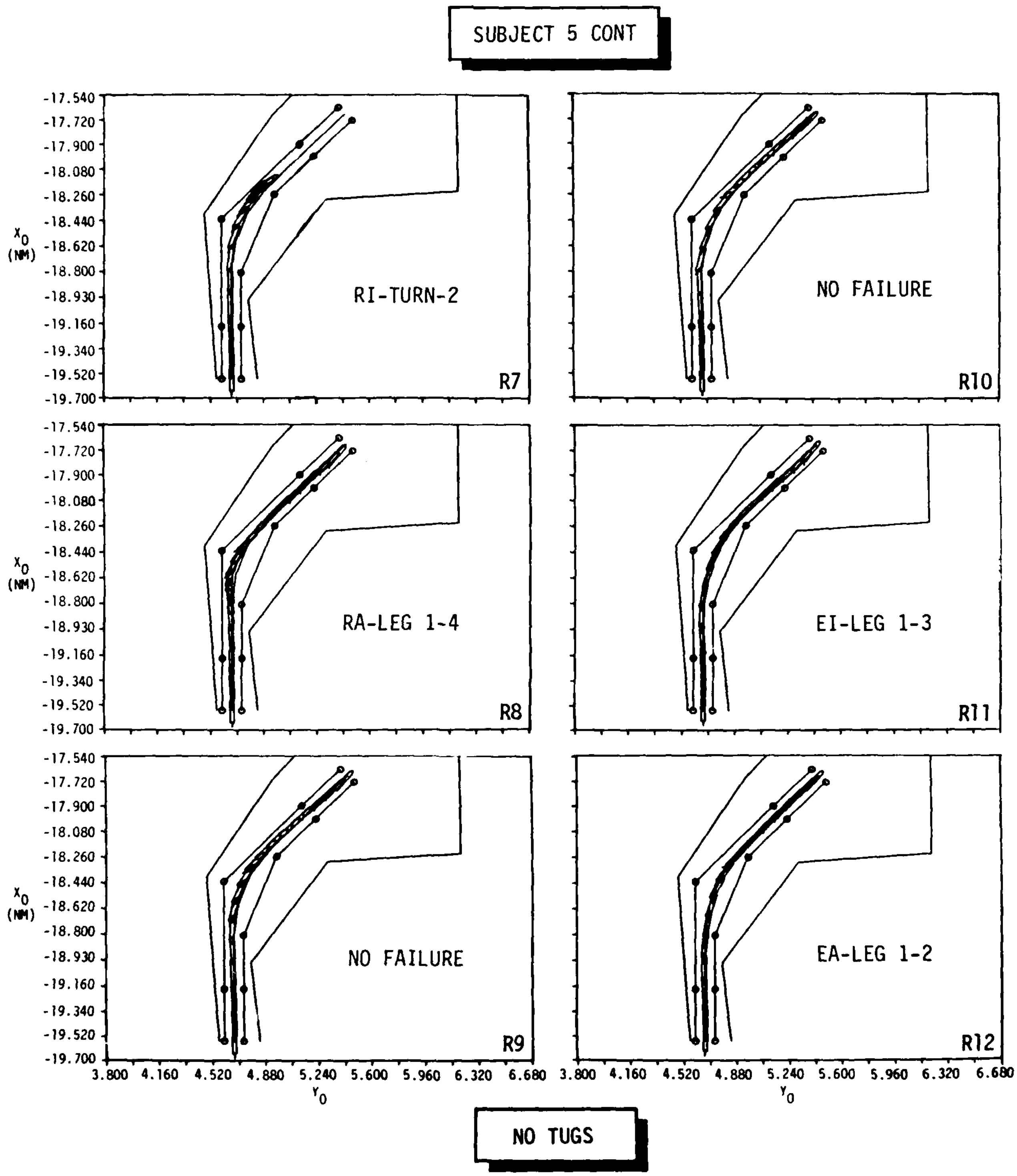


Figure 3-6 (b). Ground Tracks for Subject 5 (Cont), No Tugs, Run R7 to R12

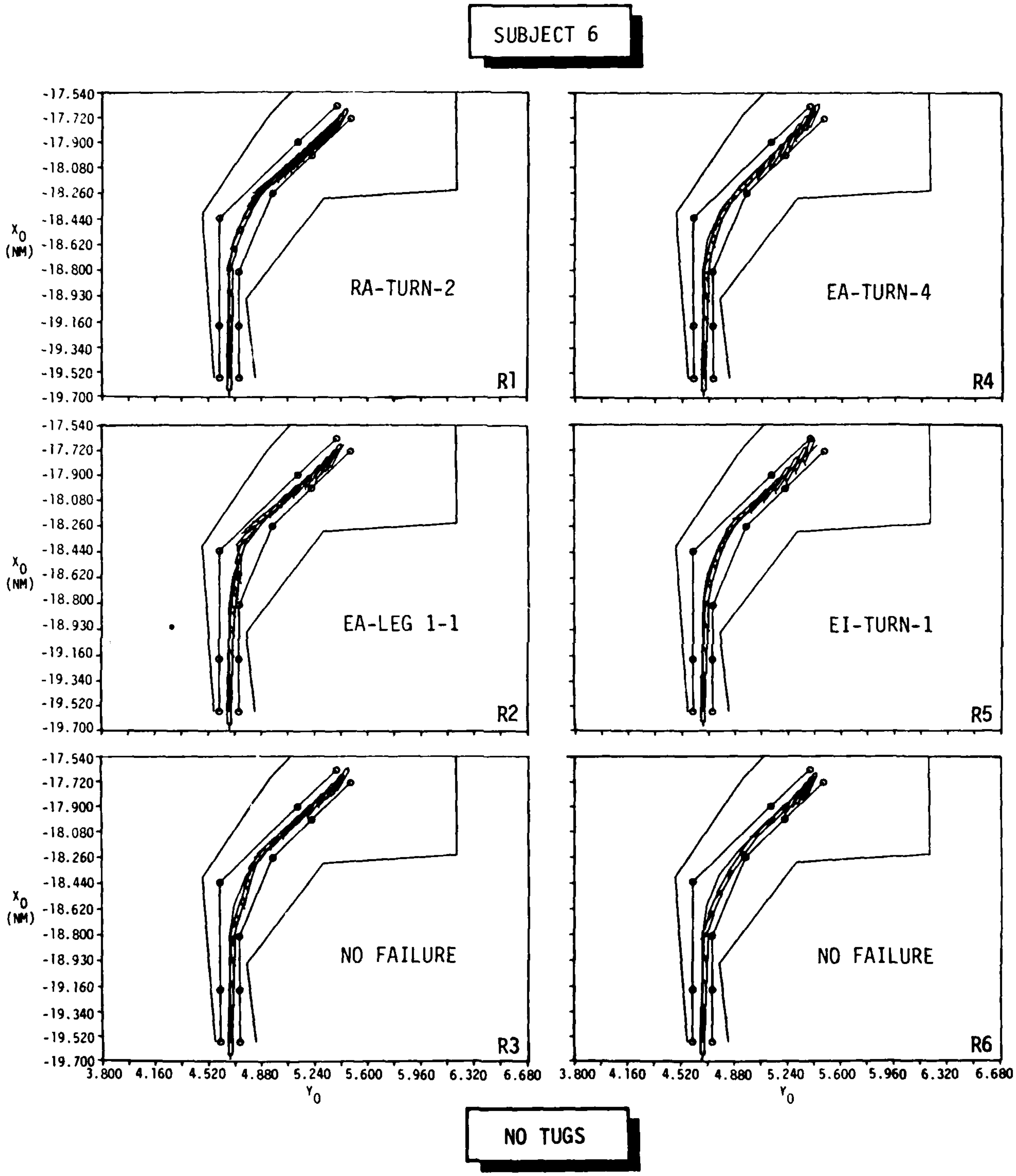


Figure 3-7 (a). Ground Tracks for Subject 6, No Tugs, Runs R1 to R6

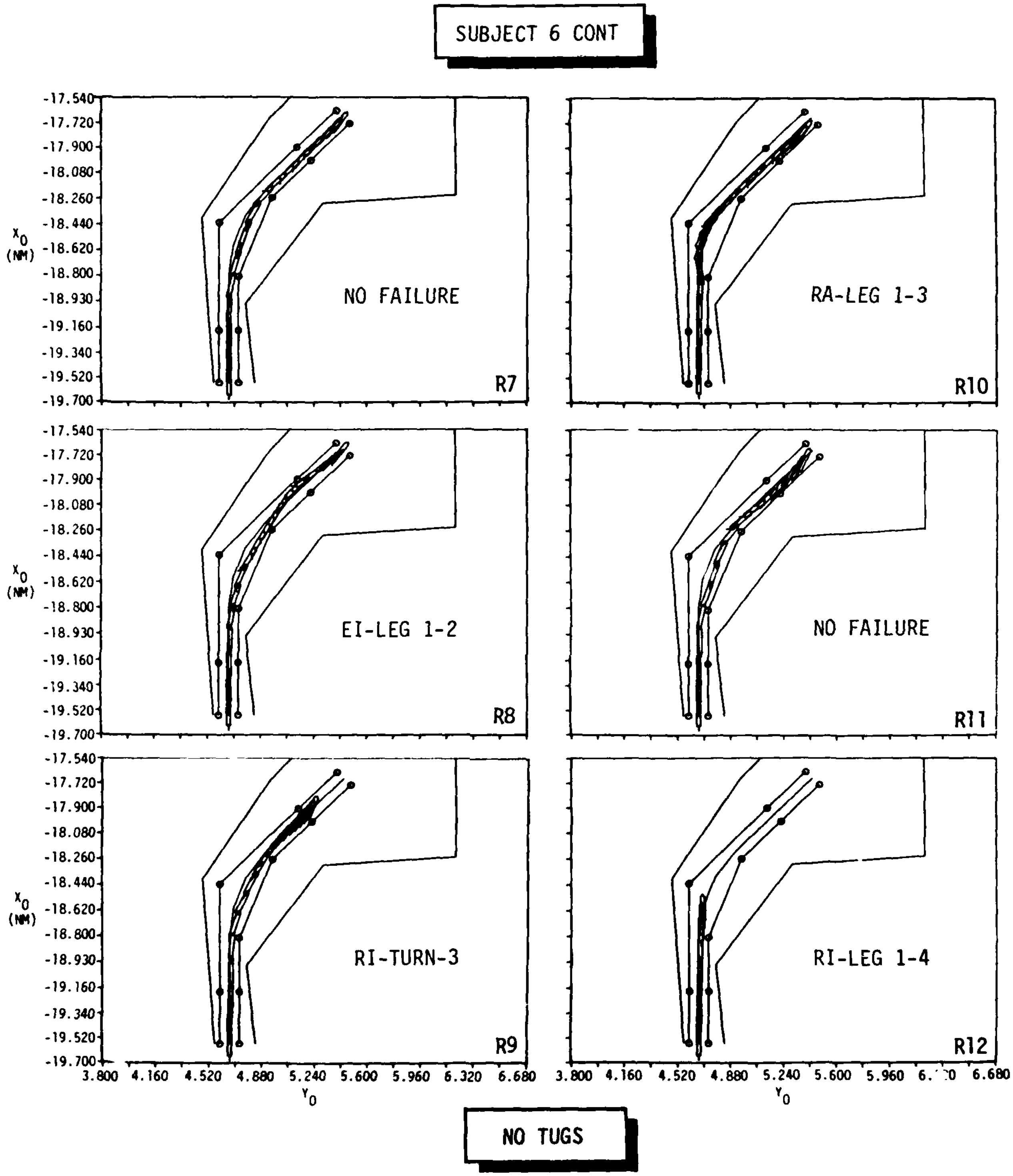


Figure 3-7 (b). Ground Tracks for Subject 6 (Cont), No Tugs, Run R7 to R12

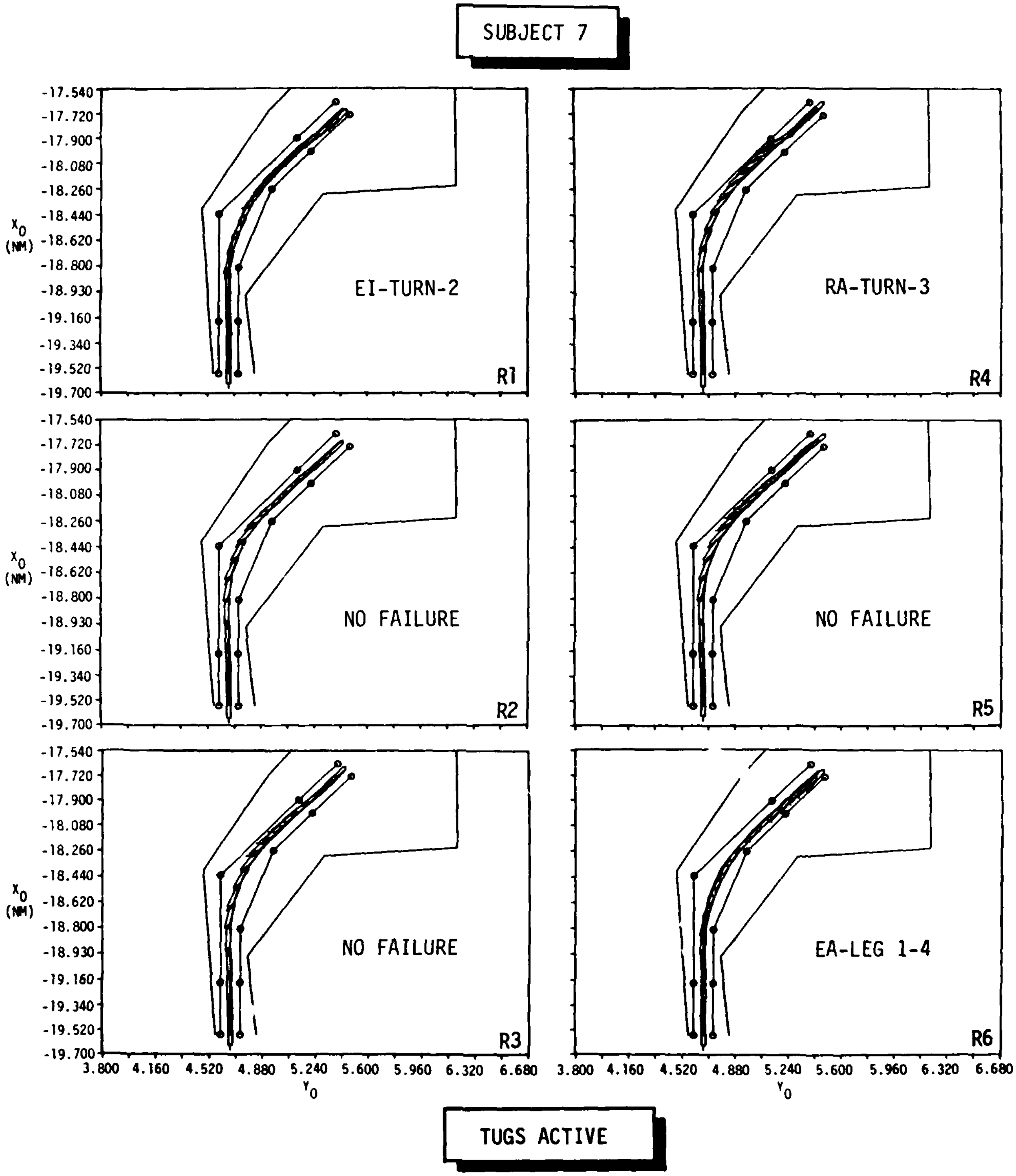


Figure 3-8 (a). Ground Tracks for Subject 7, Tugs Active, Runs R1 to R6

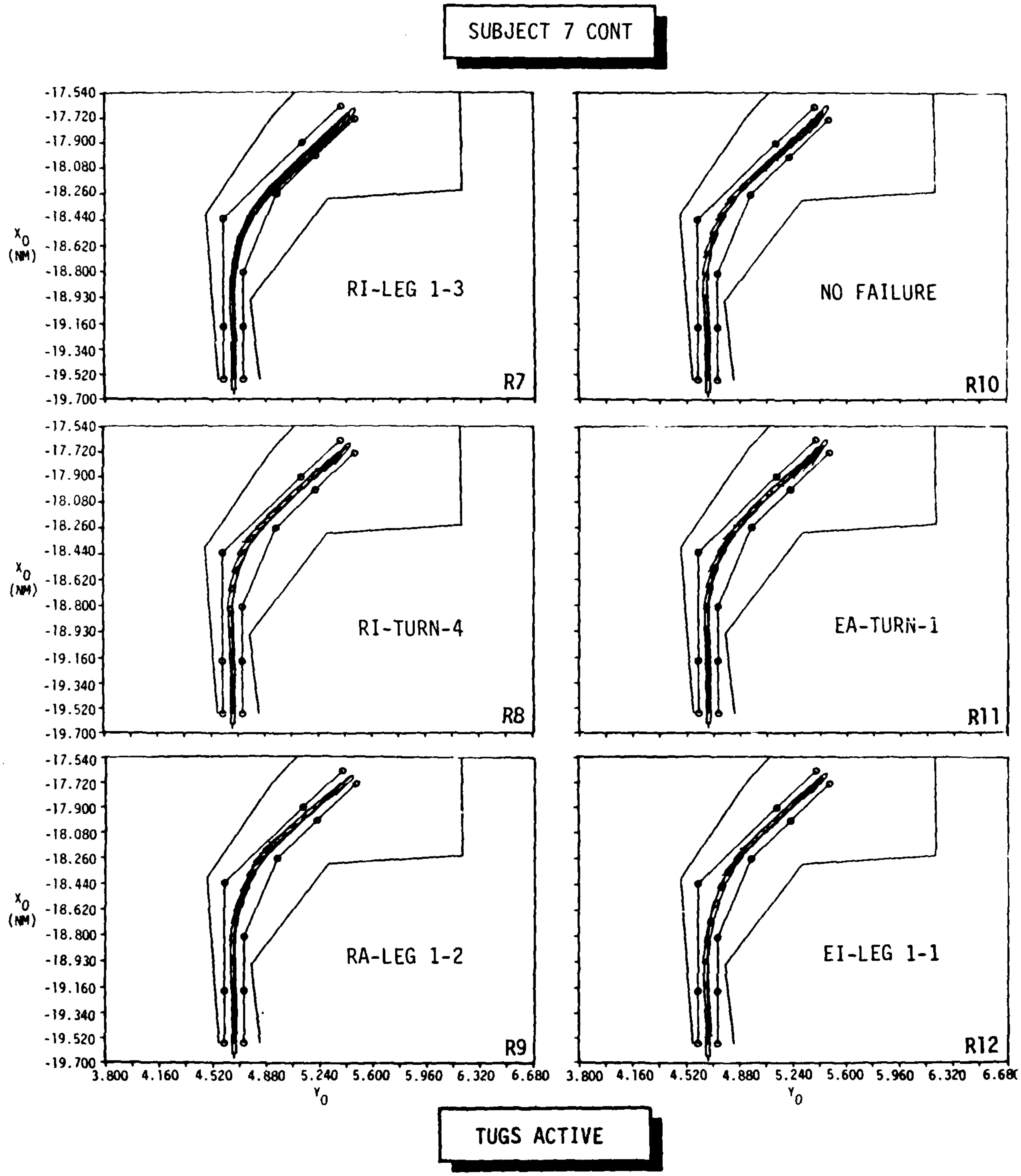


Figure 3-8 (b). Ground Tracks for Subject 7 (Cont), Tugs Active, Runs R7 to R12

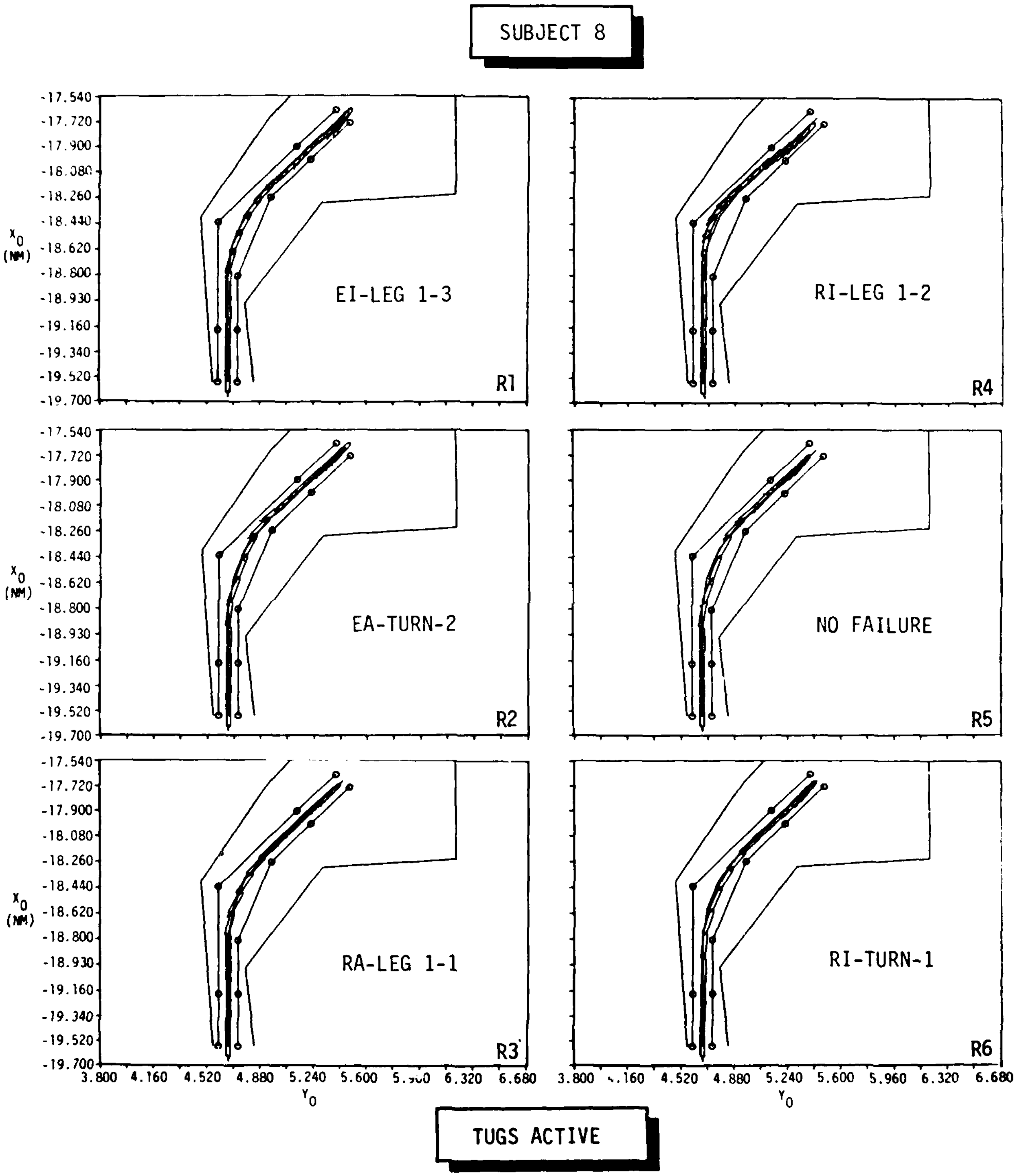


Figure 3-9 (a). Ground Tracks for Subject 8, Tugs Active, Runs R1 to R6

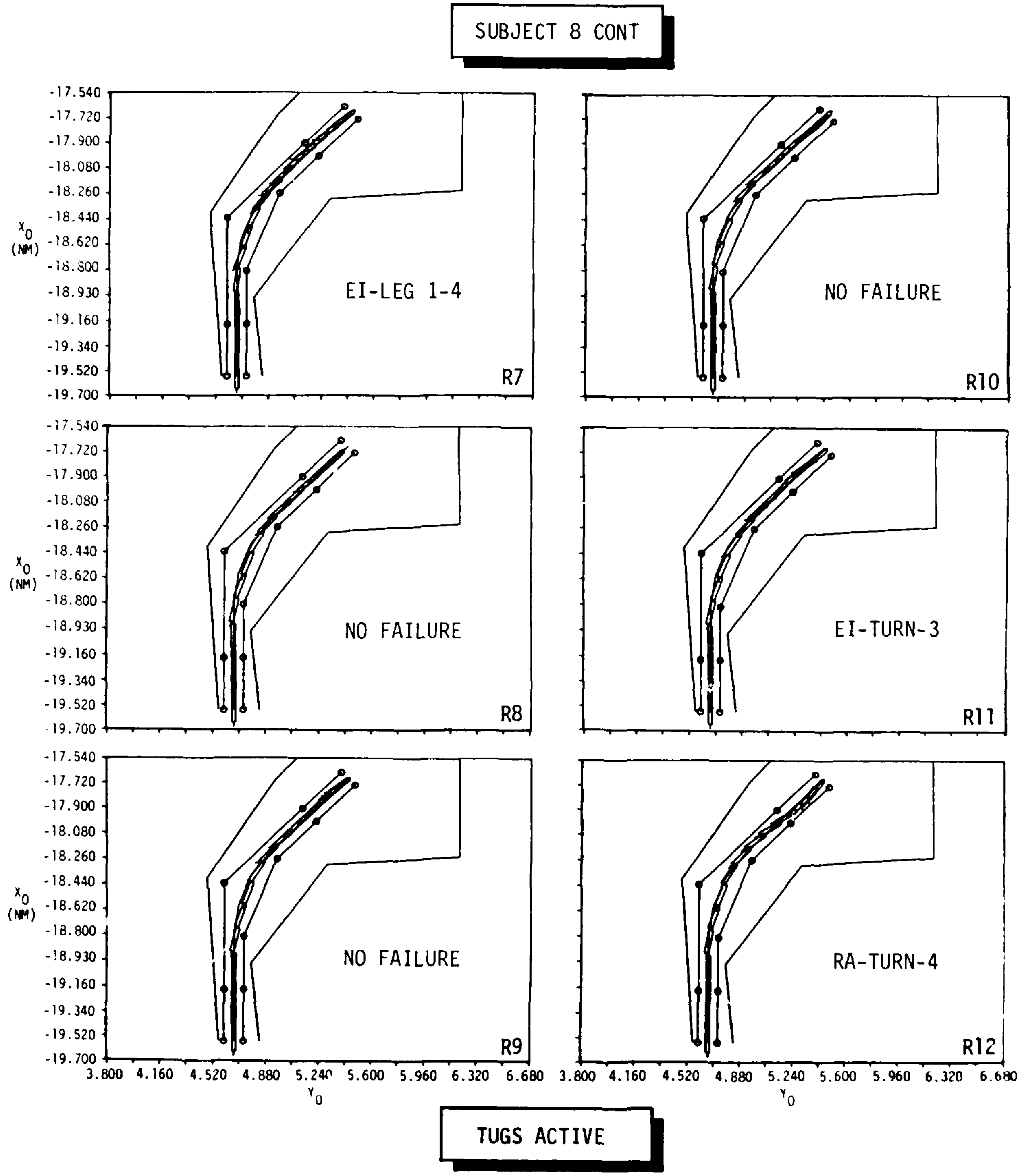


Figure 3-9 (b). Ground Tracks for Subject 8 (Cont), Tugs Active, Runs R7 to R12

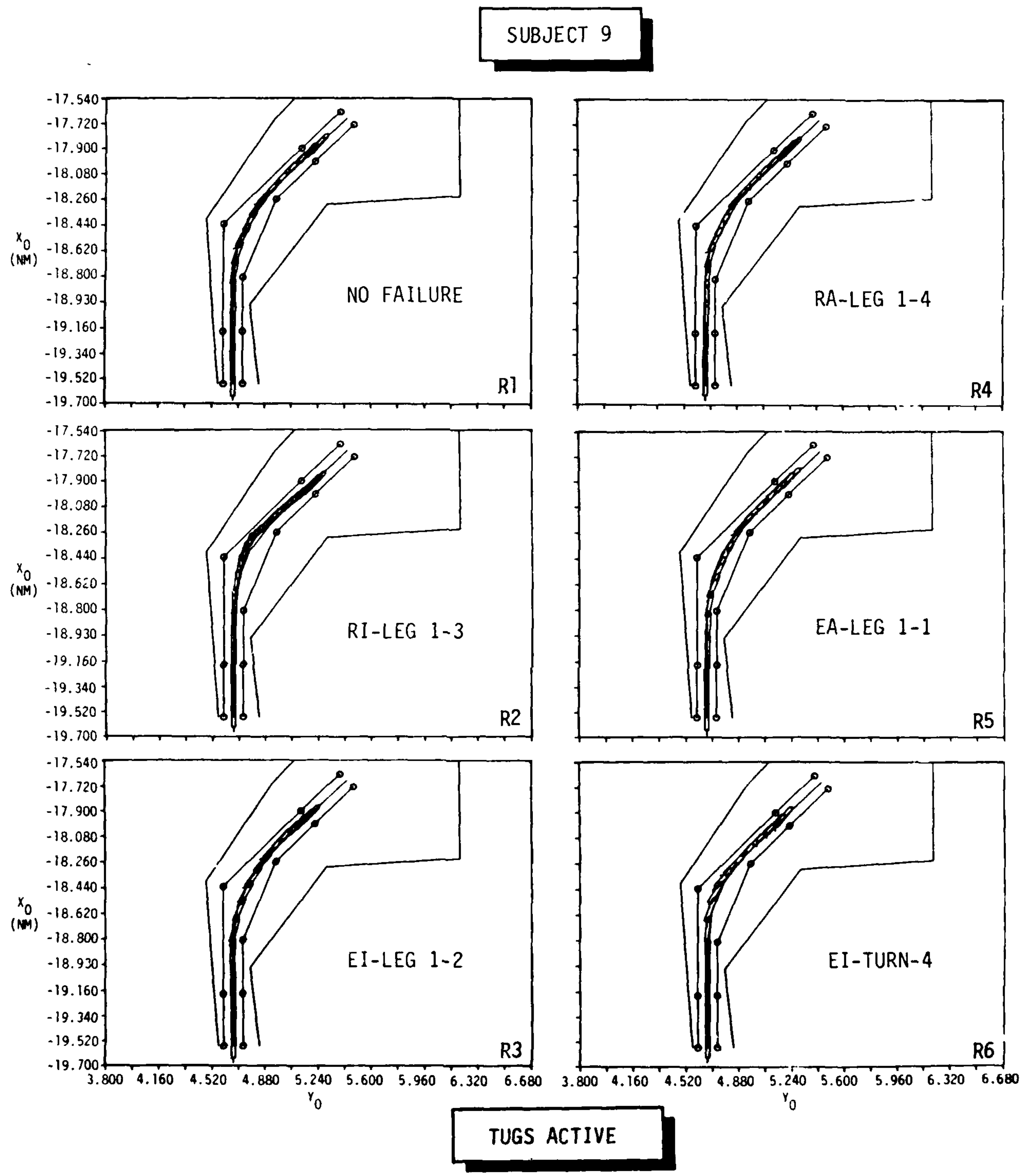


Figure 3-10 (a). Ground Tracks for Subject 9, Tugs Active, Runs R1 to R6

AD-A130 771 TUG USAGE WITH IMPAIRED MANEUVERABILITY(U) NATIONAL MARITIME RESEARCH CENTER KINGS POINT NY COMPUTER AIDED OPERATIONS RESEARCH FACILITY W MCILROY FEB 83 2/3

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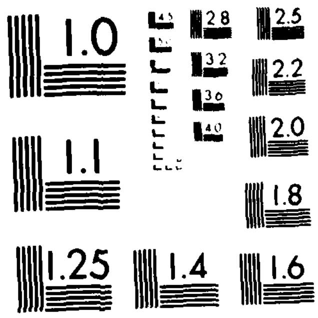
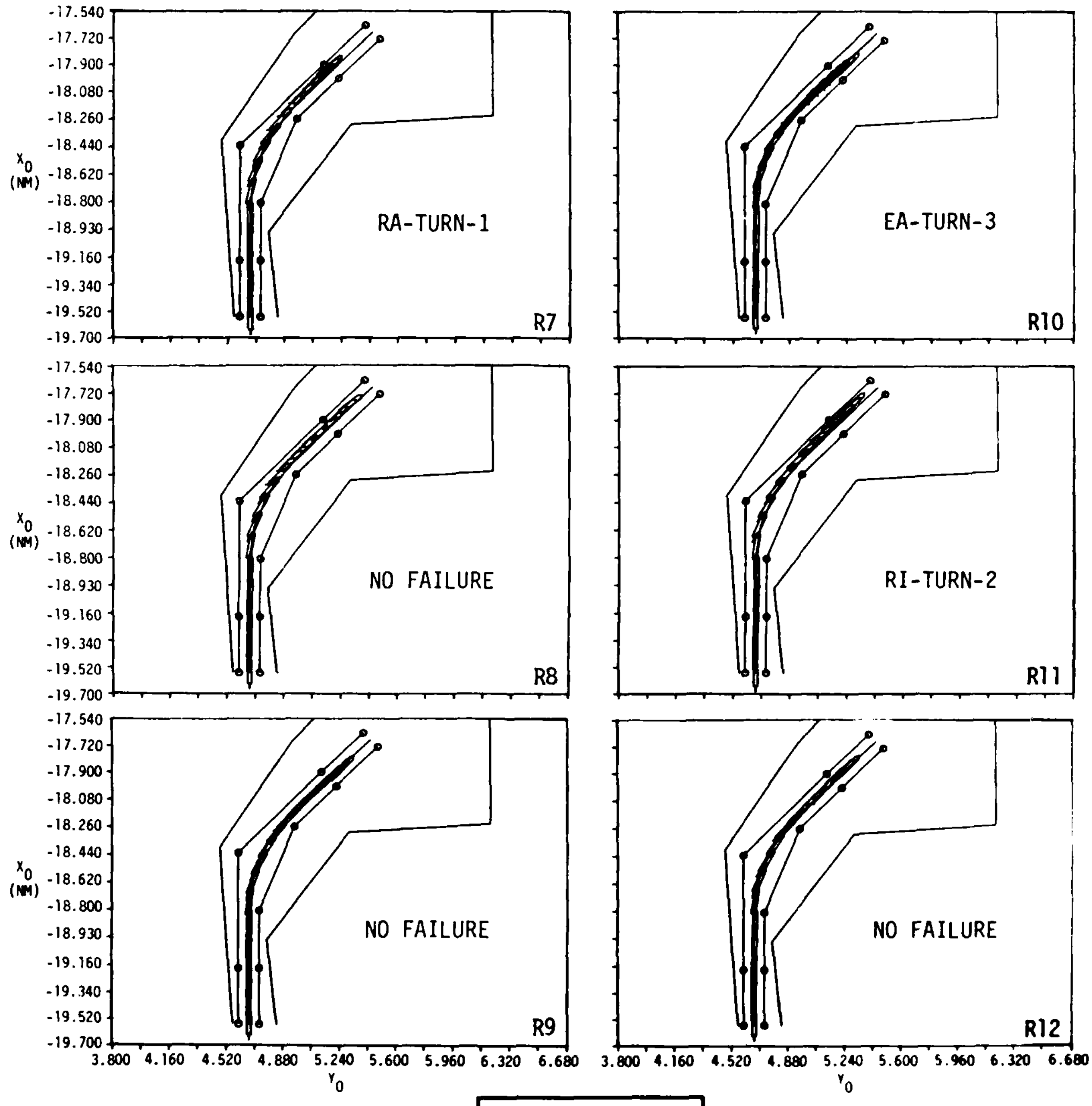


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

SUBJECT 9 CONT



TUGS ACTIVE

Figure 3-10 (b). Ground Tracks for Subject 9 (Cont), Tugs Active, Runs R7 to R12

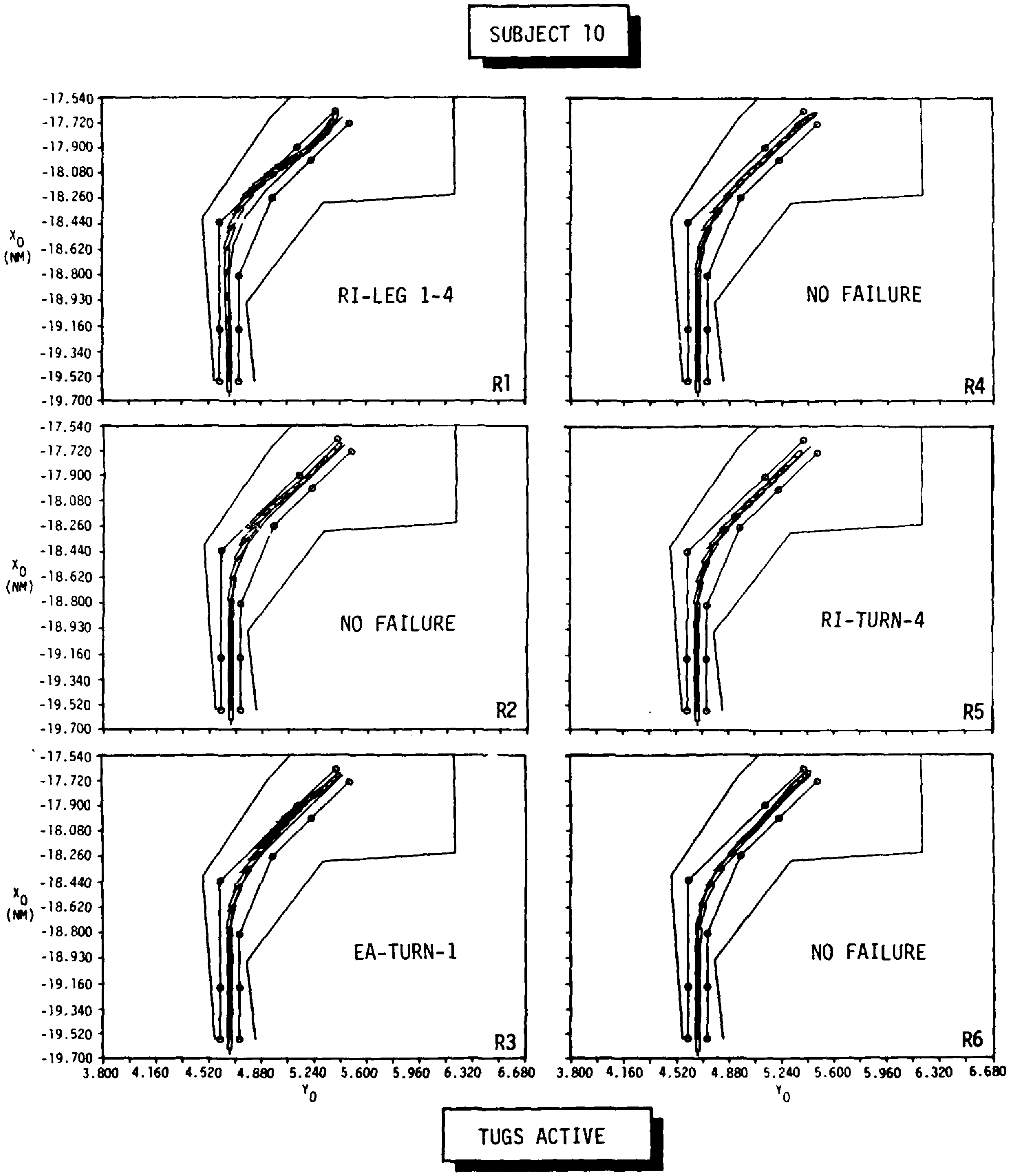


Figure 3-11 (a). Ground Tracks for Subject 10, Tugs Active, Runs R1 to R6

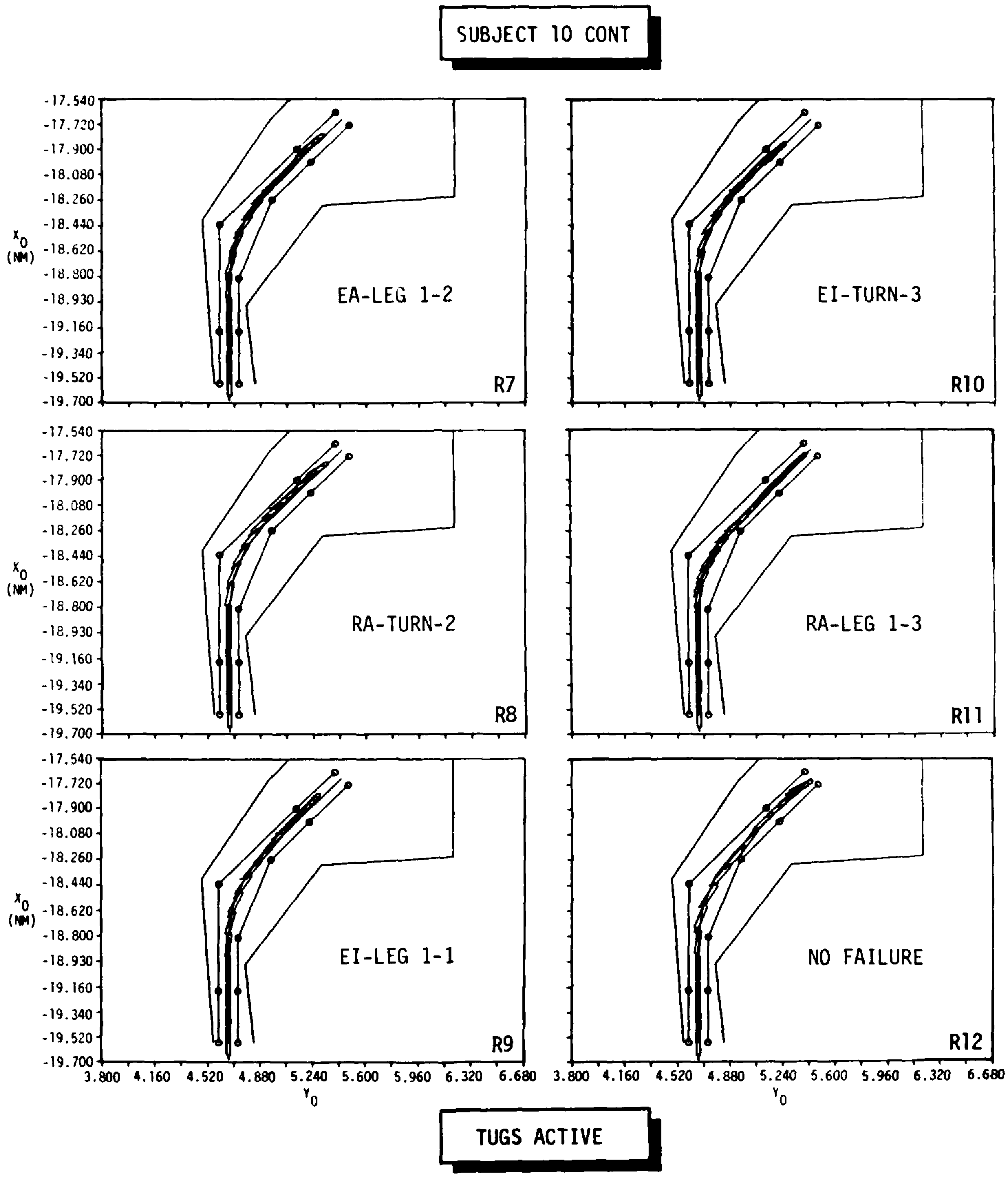


Figure 3-11 (b). Ground Tracks for Subject 10 (Cont), Tugs Active, Runs R7 to R12

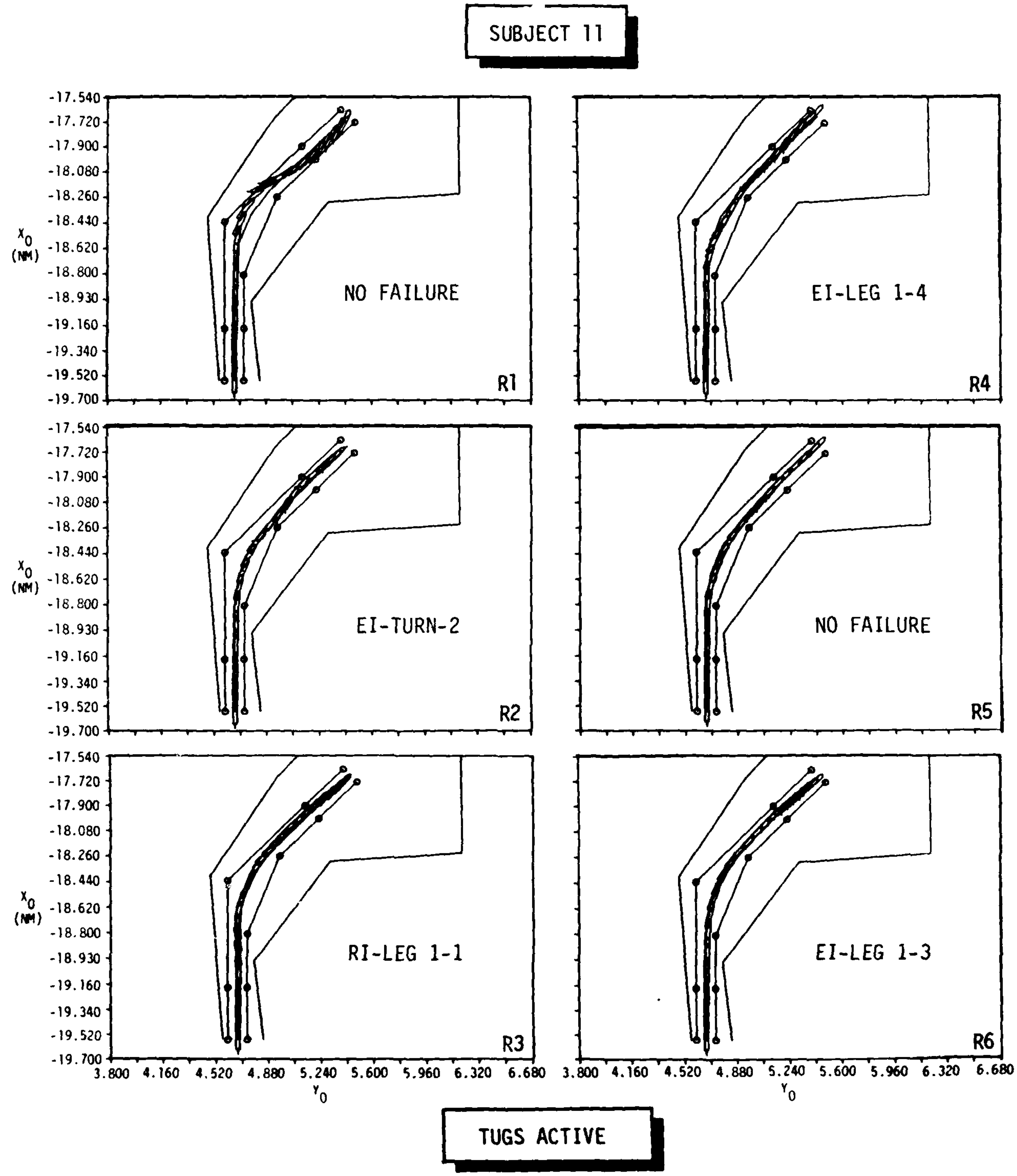


Figure 3-12 (a). Ground Tracks for Subject 11, Tugs Active, Runs R1 to R6

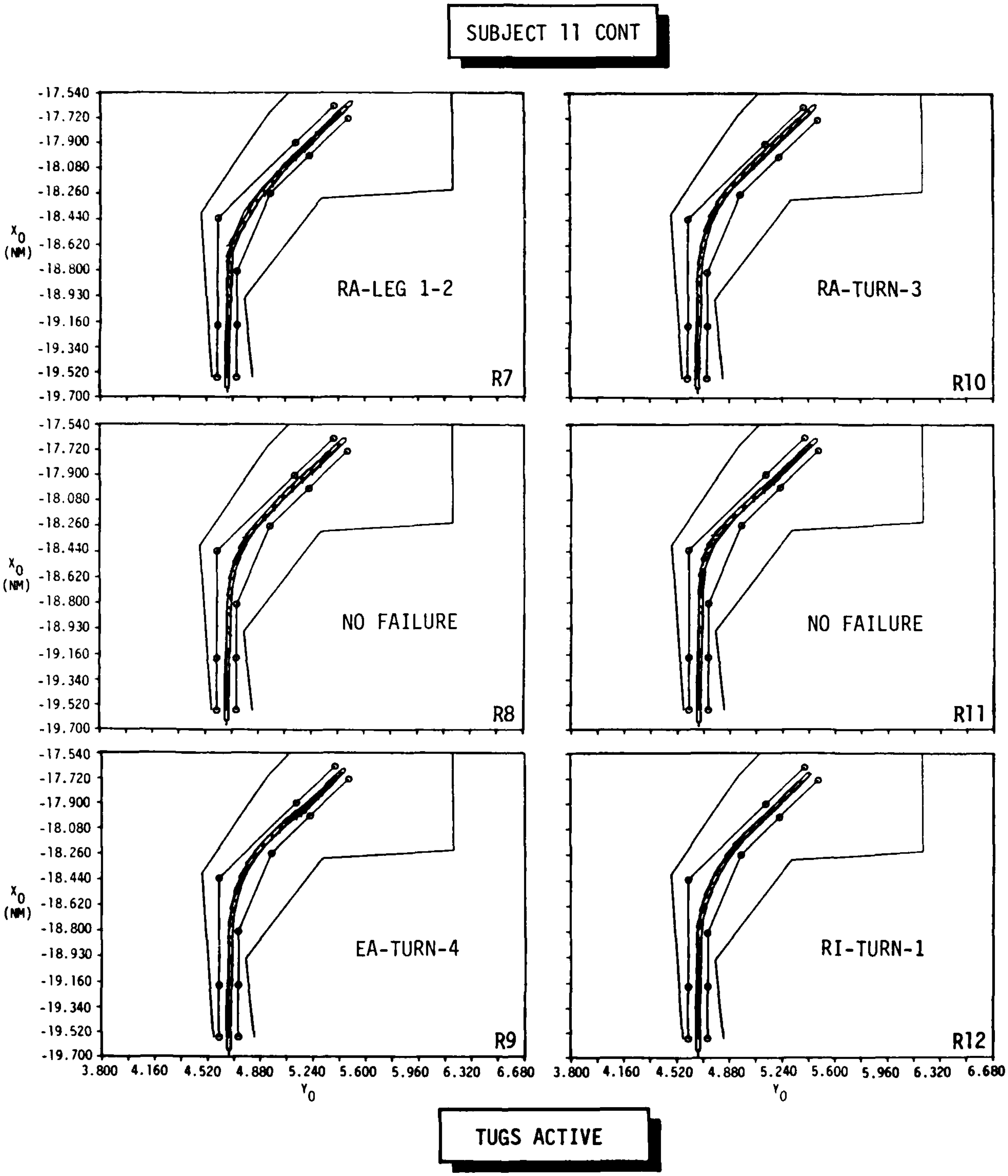


Figure 3-12 (b). Ground Tracks for Subject 11 (Cont), Tugs Active, Runs R7 to R12

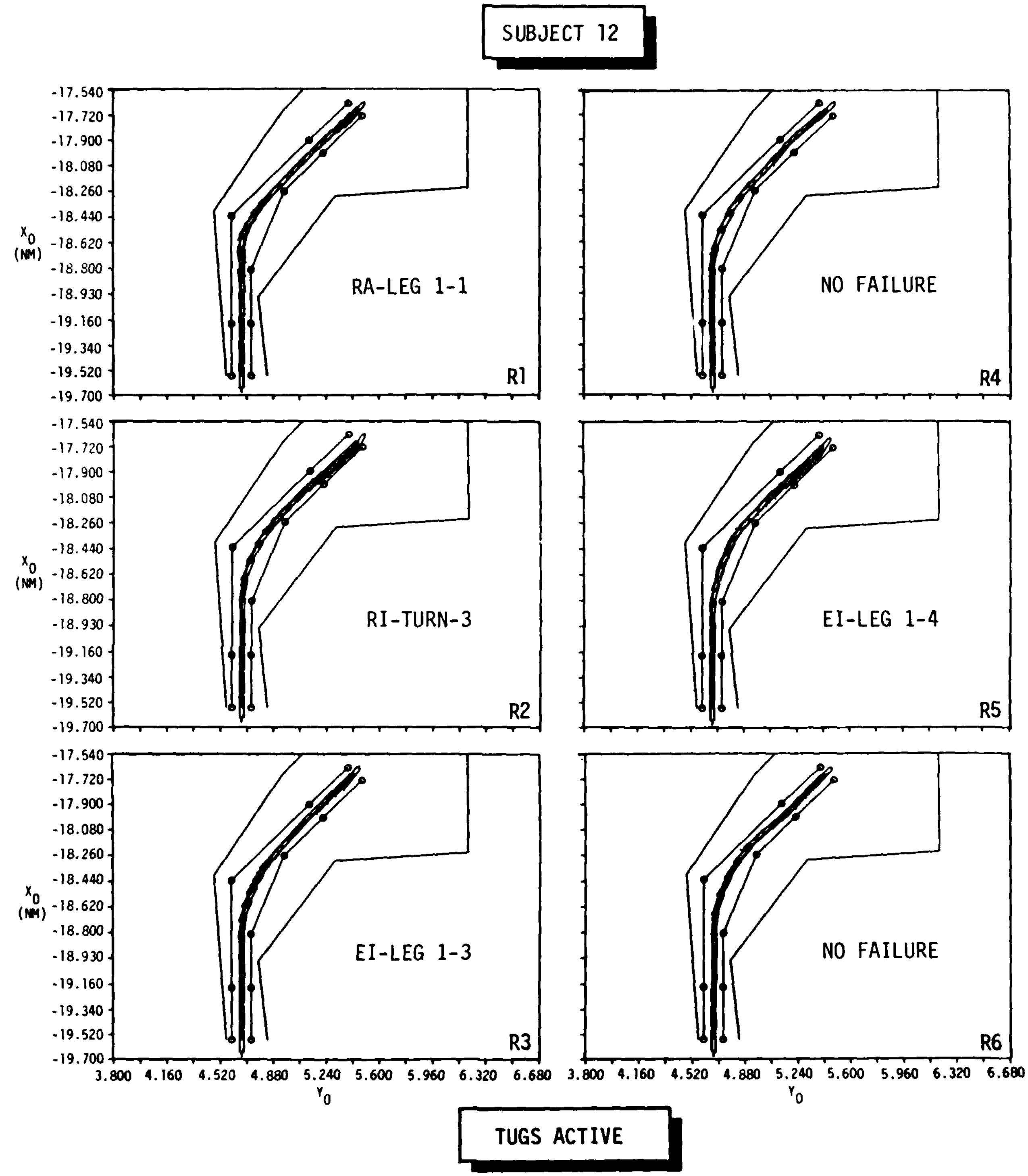


Figure 3-13 (a). Ground Tracks for Subject 12, Tugs Active, Runs R1 to R6

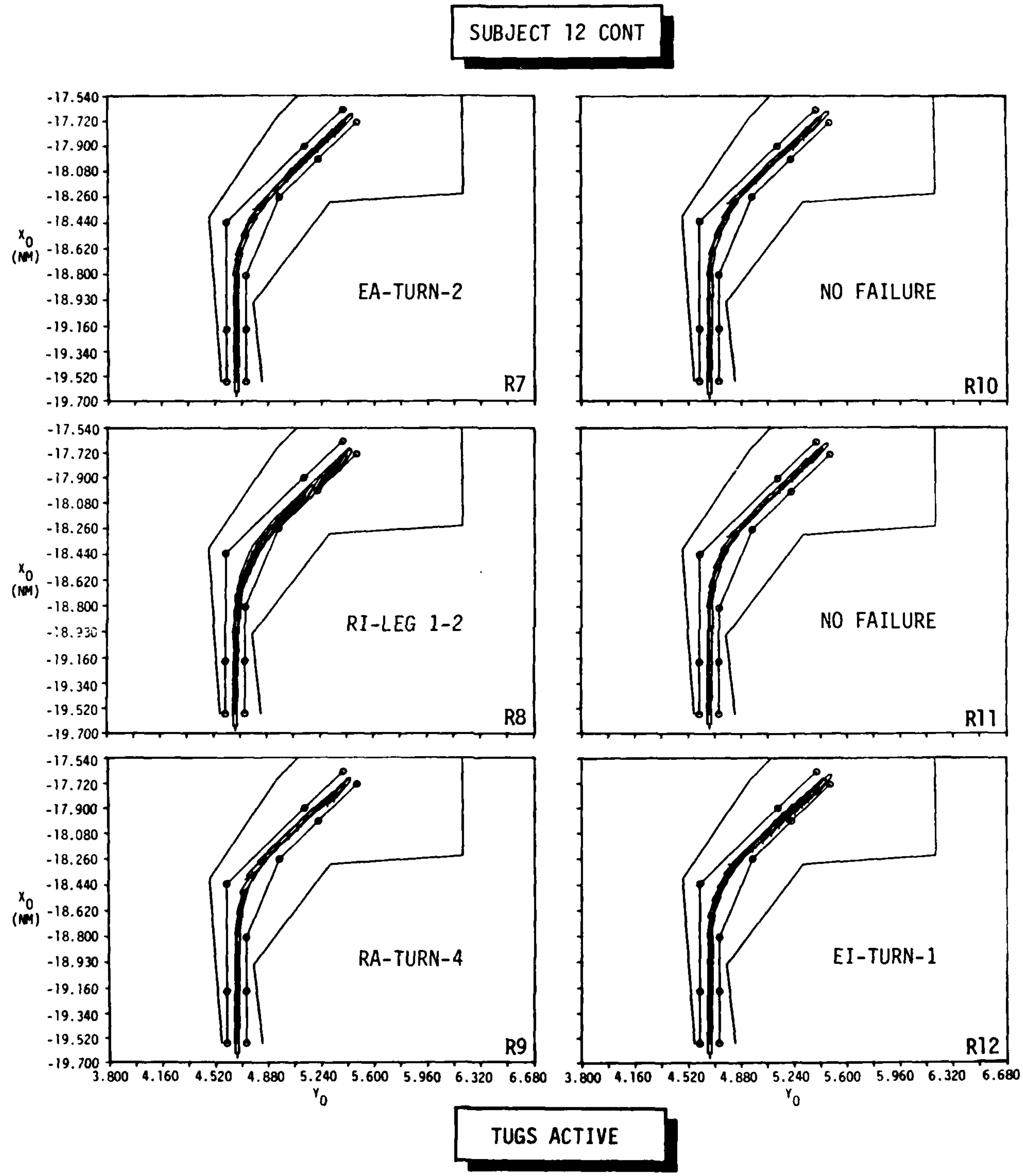


Figure 3-13 (b). Ground Tracks for Subject 12 (Cont), Tugs Active, Runs R7 to R12

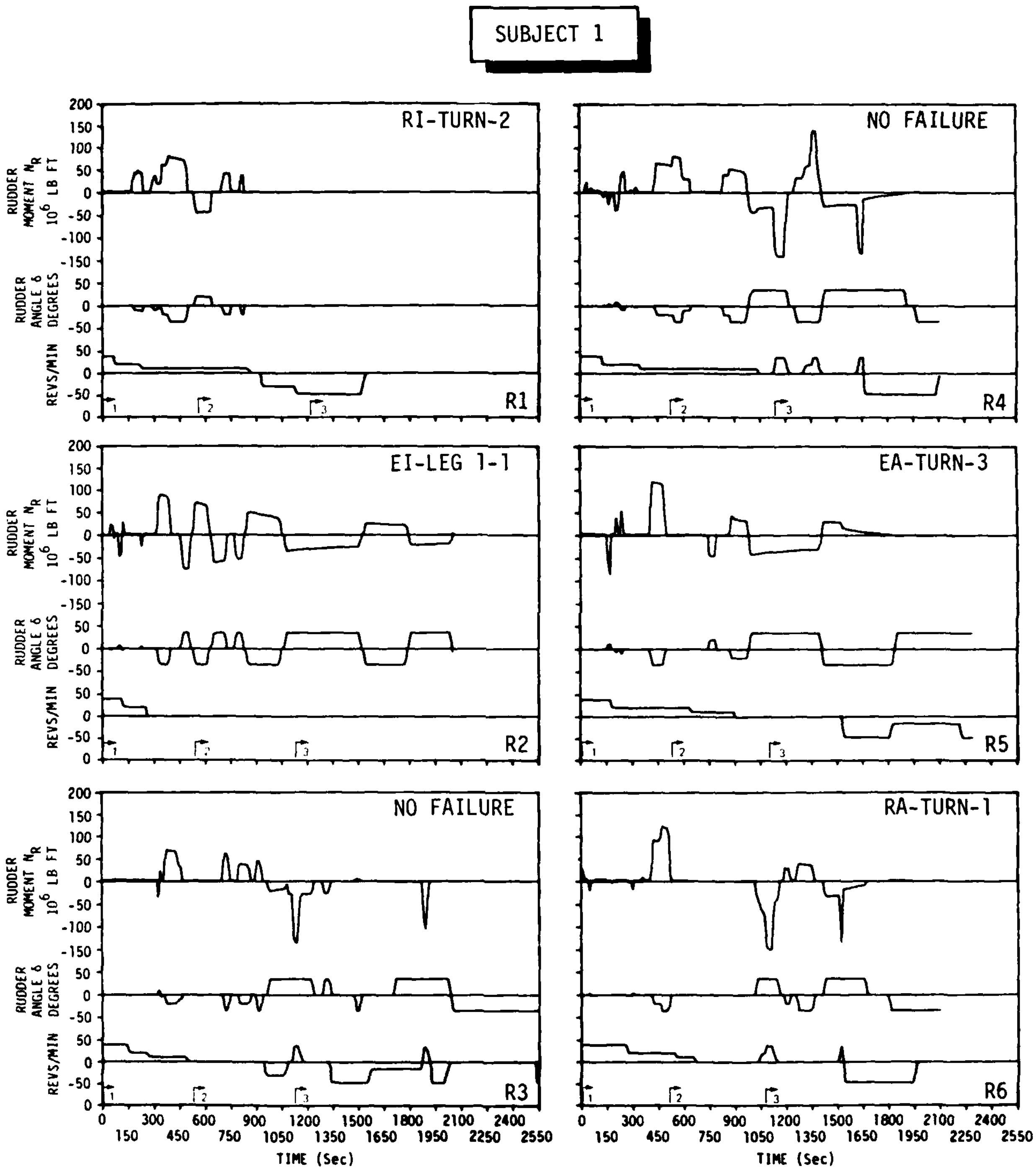


Figure 3-14 (a). Time Variation in Rudder Moment, Rudder Angle and RPM, No Tug Mode, Subject 1, Runs R1 to R6

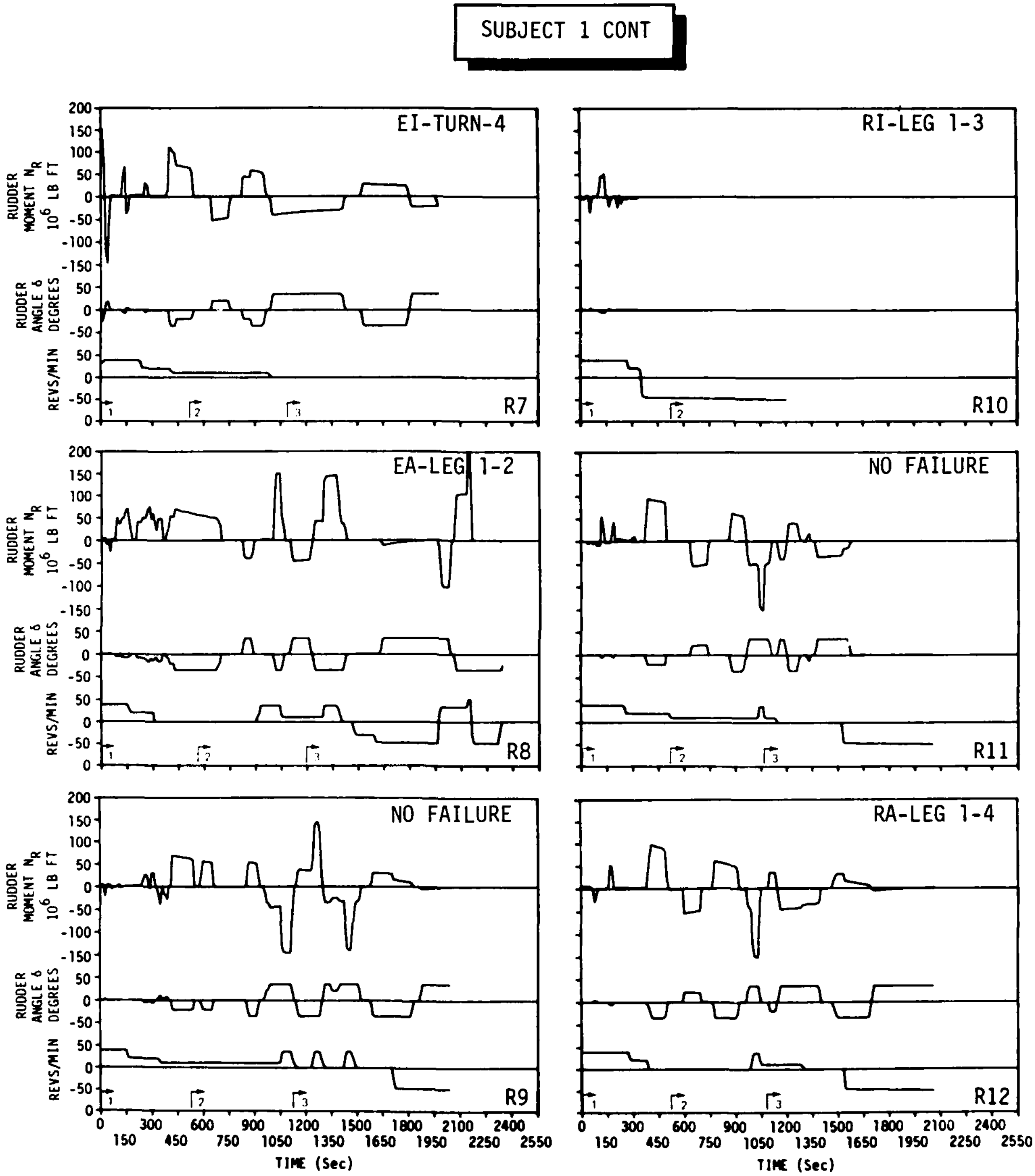


Figure 3-14 (b). Time Variation in Rudder Moment, Rudder Angle and RPM, No Tug Mode, Subject 1 (Cont), Runs R7 to R12

SUBJECT 2

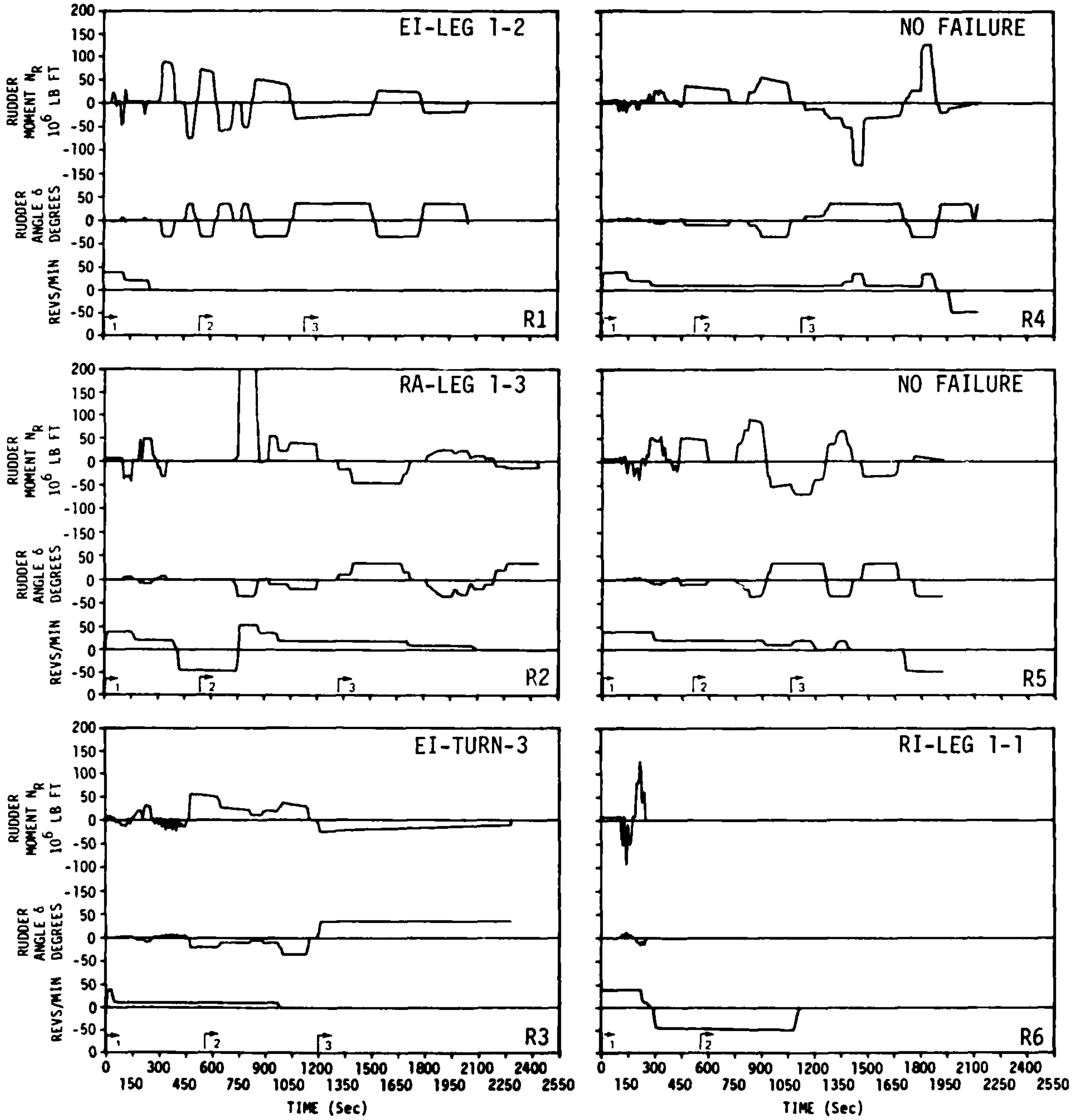


Figure 3-15 (a). Time Variation in Rudder Moment, Rudder Angle and RPM, No Tug Mode, Subject 2, Runs R1 to R6

SUBJECT 2 CONT

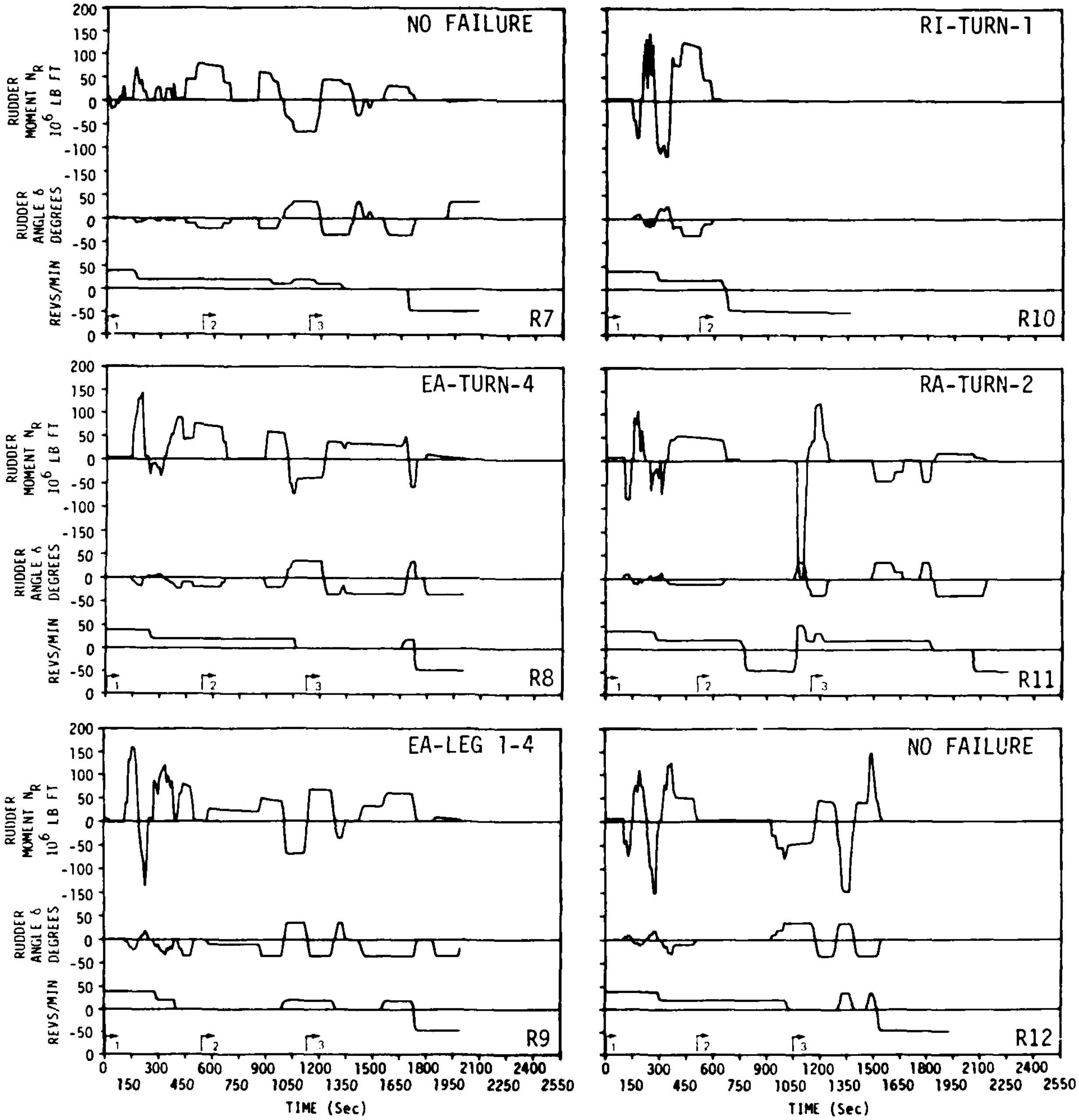


Figure 3-15 (b). Time Variation in Rudder Moment, Rudder Angle and RPM, No Tug Mode, Subject 2 (Cont), Runs R7 to R12

SUBJECT 3

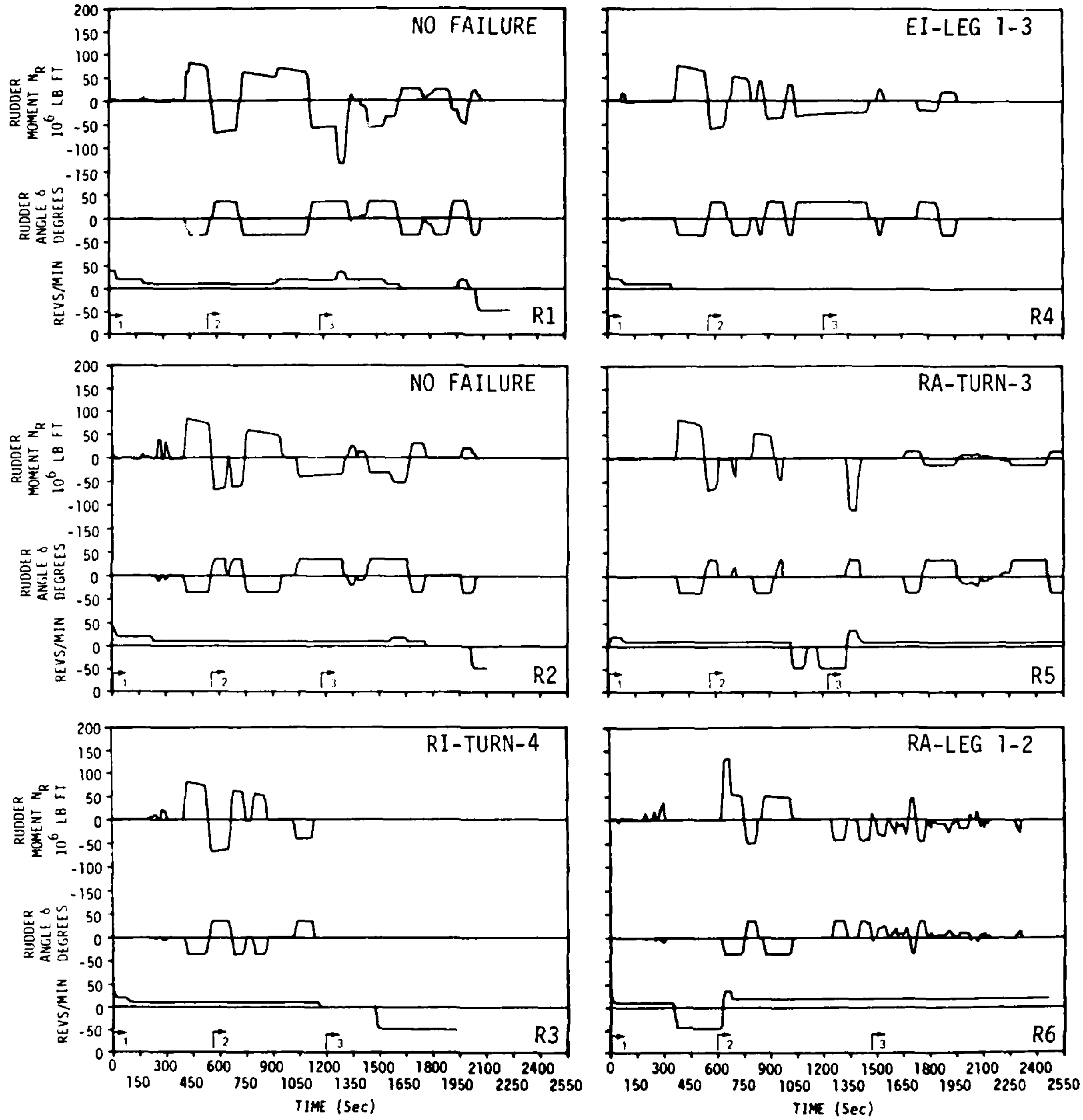


Figure 3-16 (a). Time Variation in Rudder Moment, Rudder Angle and RPM, No Tug Mode, Subject 3, Runs R1 to R6

SUBJECT 3 CONT

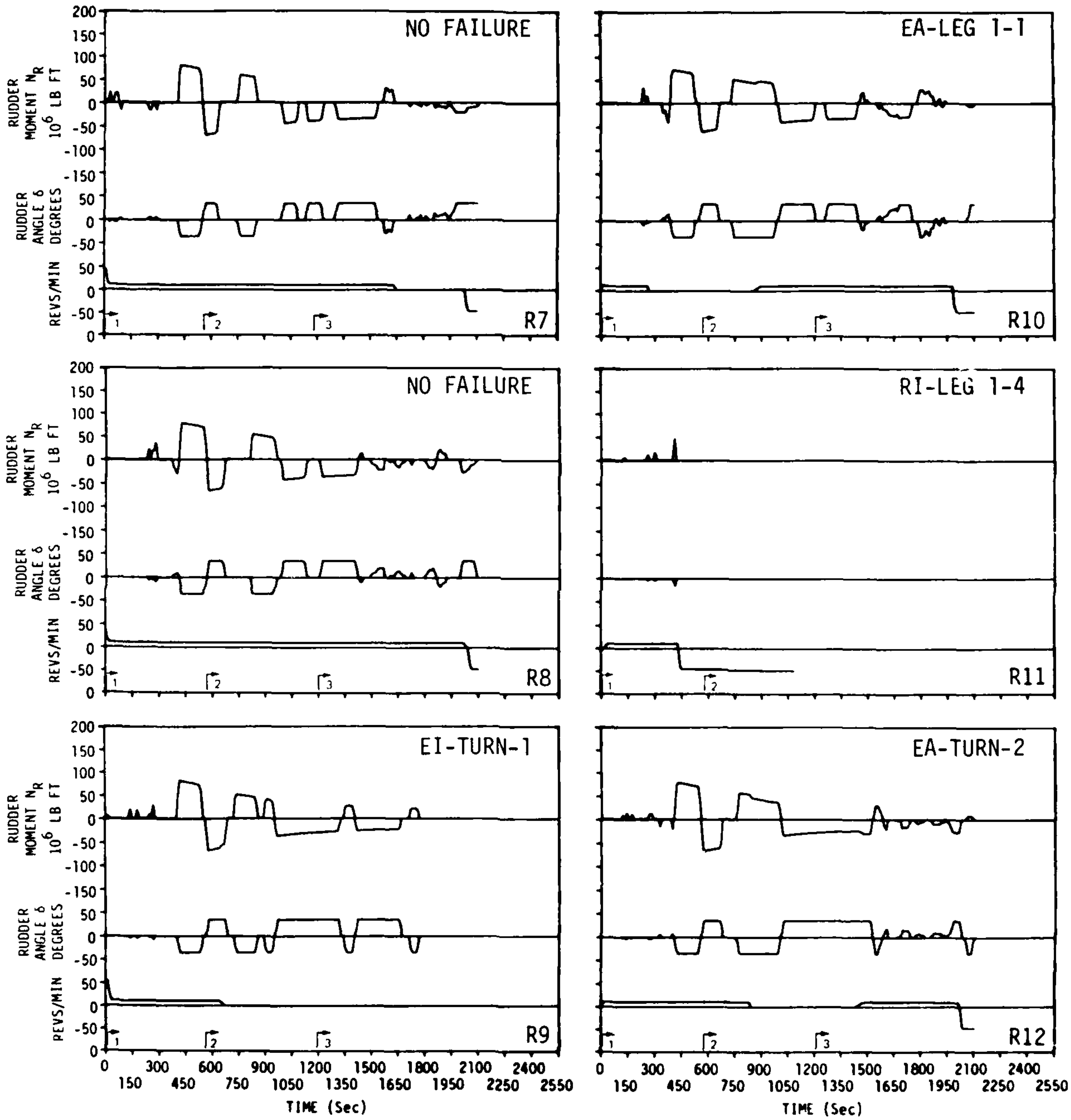


Figure 3-16 (b). Time Variation in Rudder Moment, Rudder Angle and RPM, No Tug Mode, Subject 3 (Cont), Runs R7 to R12

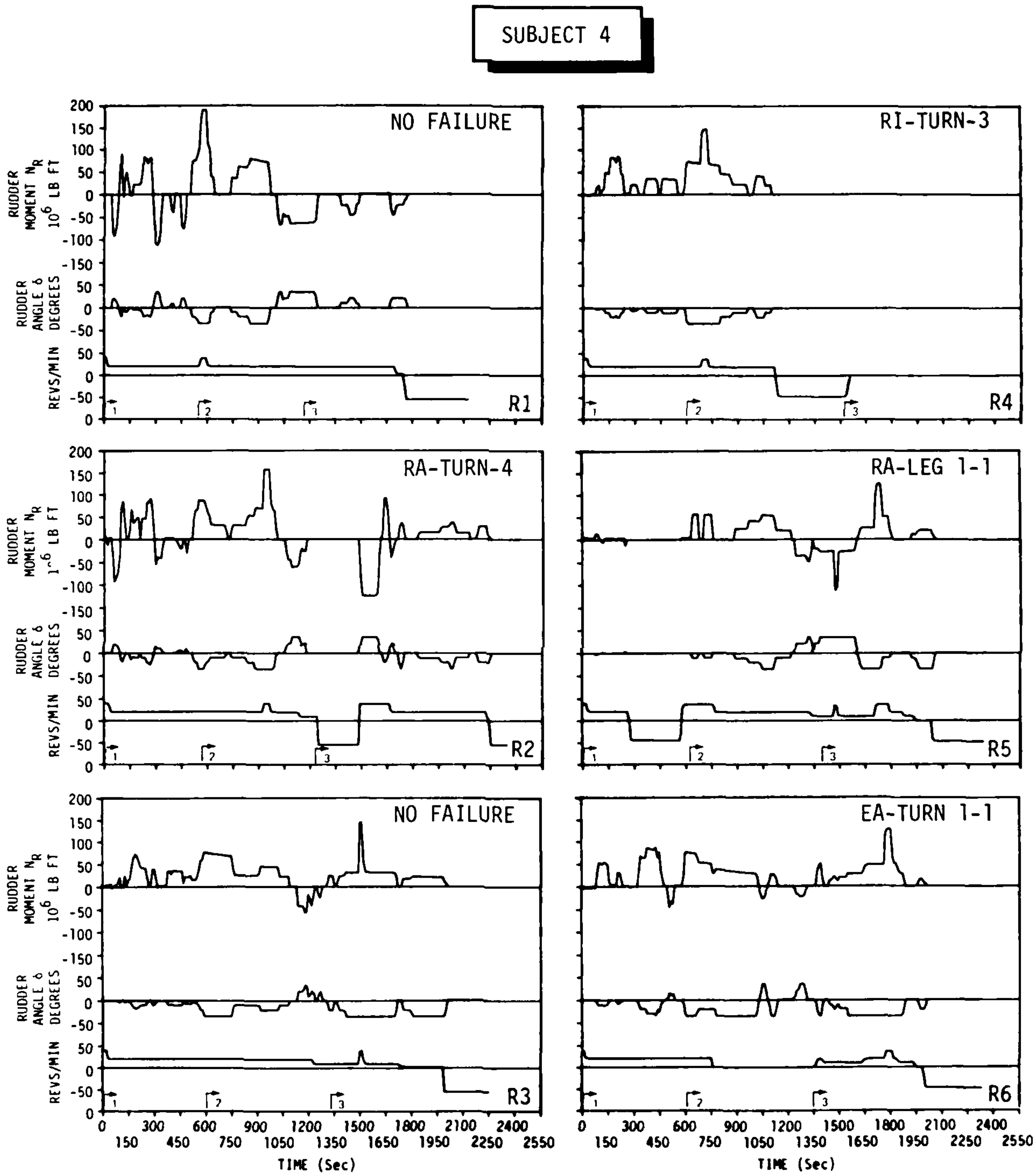


Figure 3-17 (a). Time Variation in Rudder Moment, Rudder Angle and RPM, No Tug Mode, Subject 4, Runs R1 to R6

SUBJECT 4 CONT

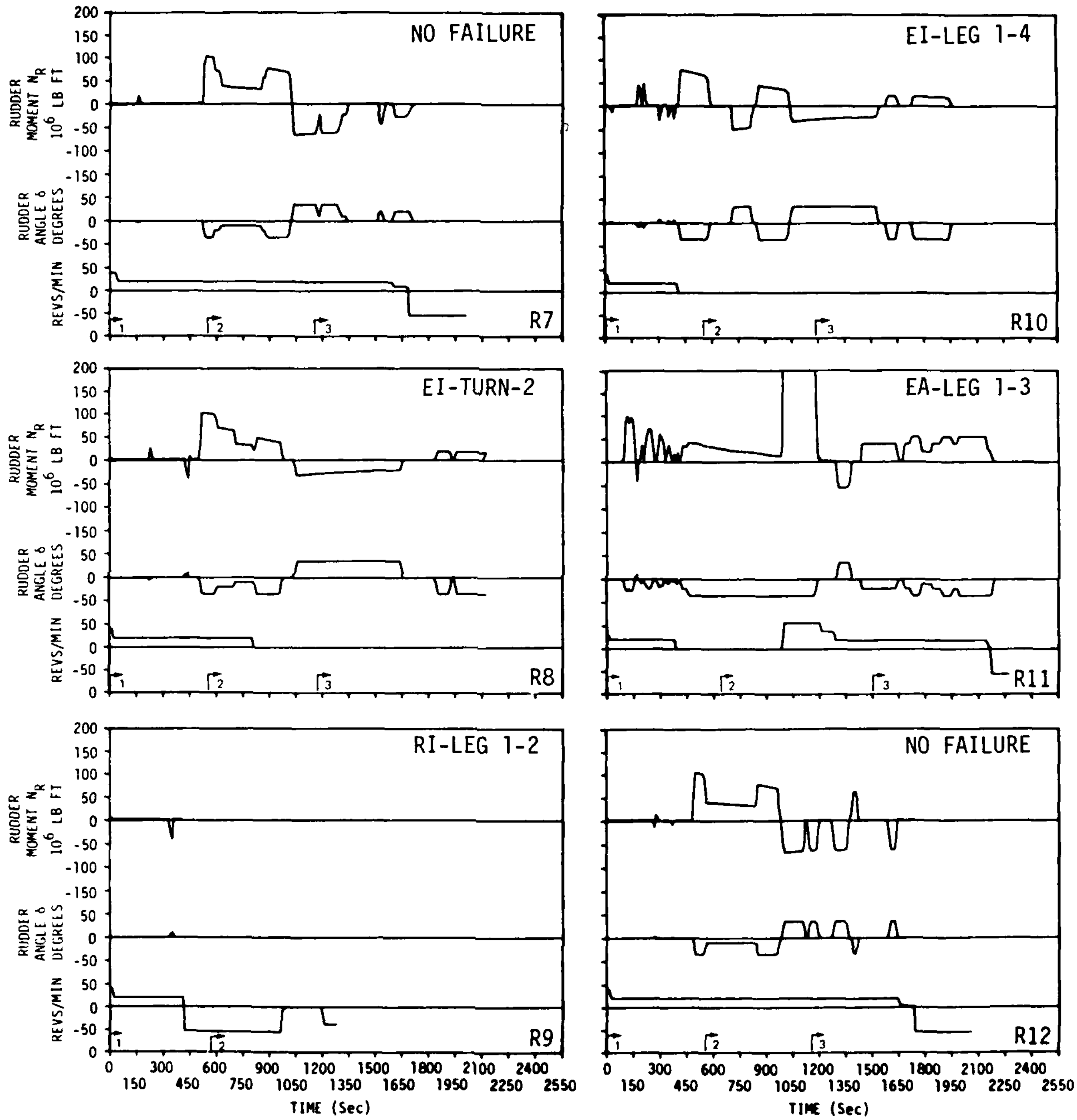


Figure 3-17 (b). Time Variation in Rudder Moment, Rudder Angle and RPM, No Tug Mode, Subject 4 (Cont), Runs R7 to R12

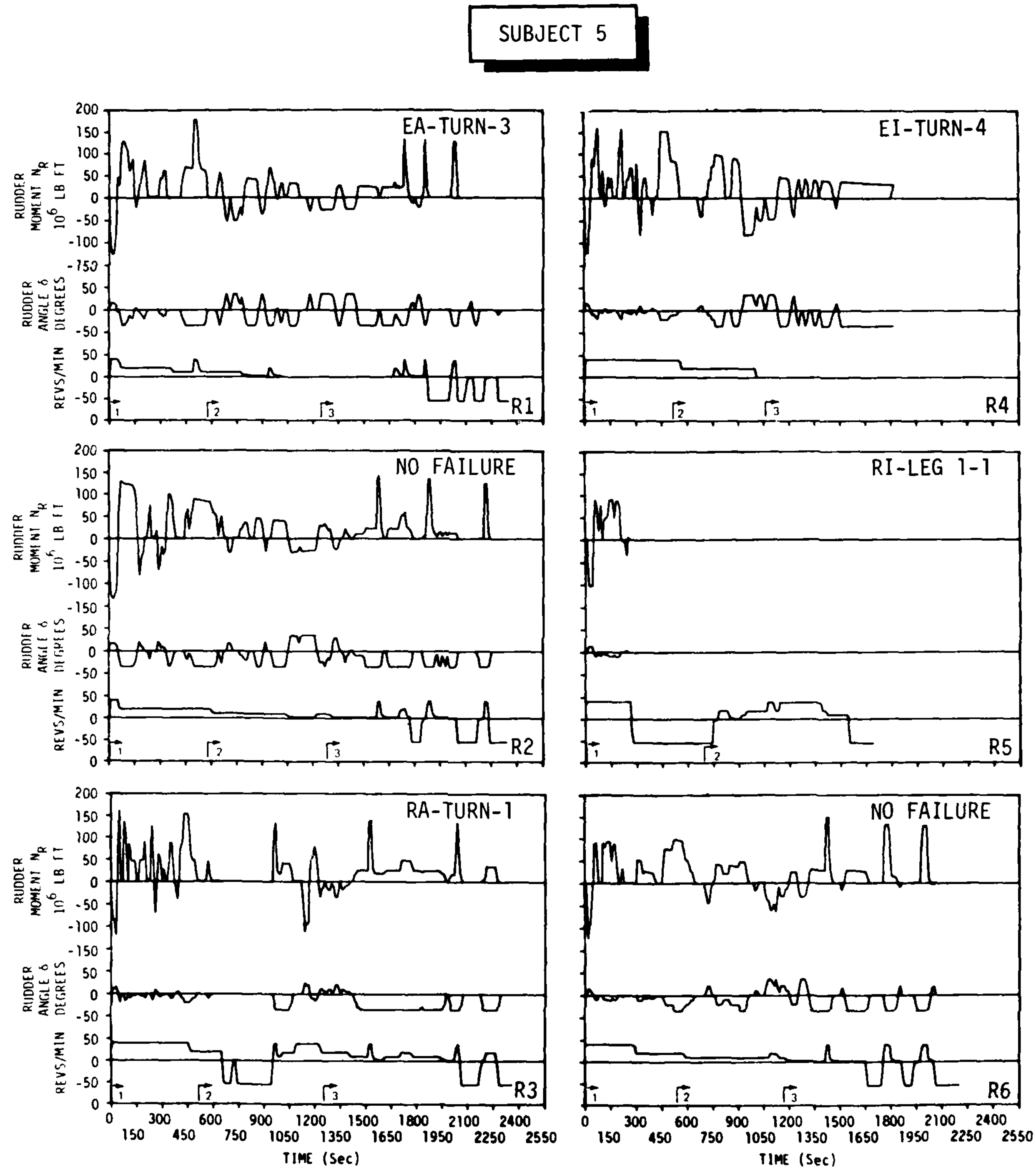


Figure 3-18 (a). Time Variation in Rudder Moment, Rudder Angle and RPM, No Tug Mode, Subject 5, Runs R1 to R6

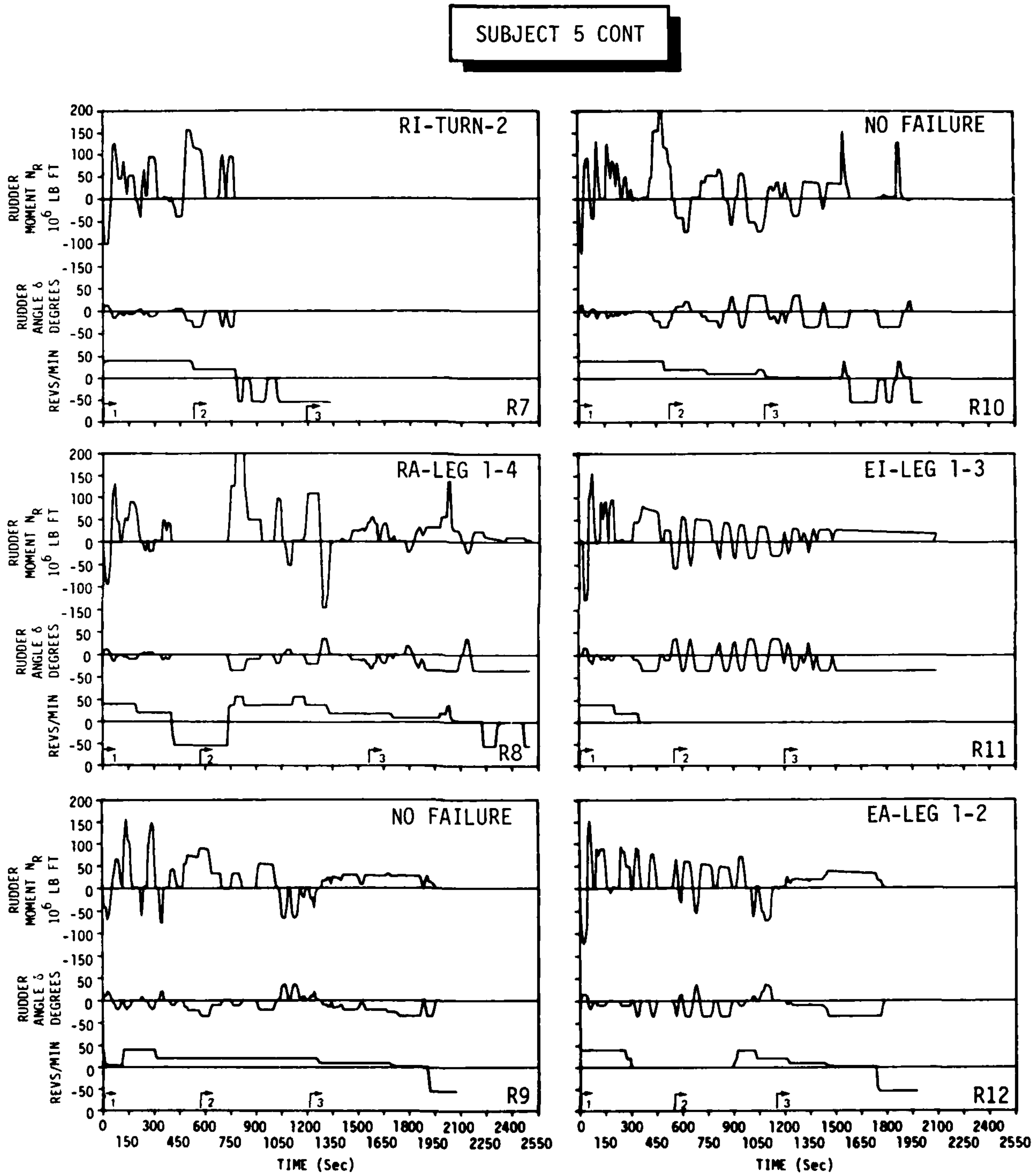


Figure 3-18 (b). Time Variation in Rudder Moment, Rudder Angle and RPM, No Tug Mode, Subject 5 (Cont), Runs R7 to R12

SUBJECT 6

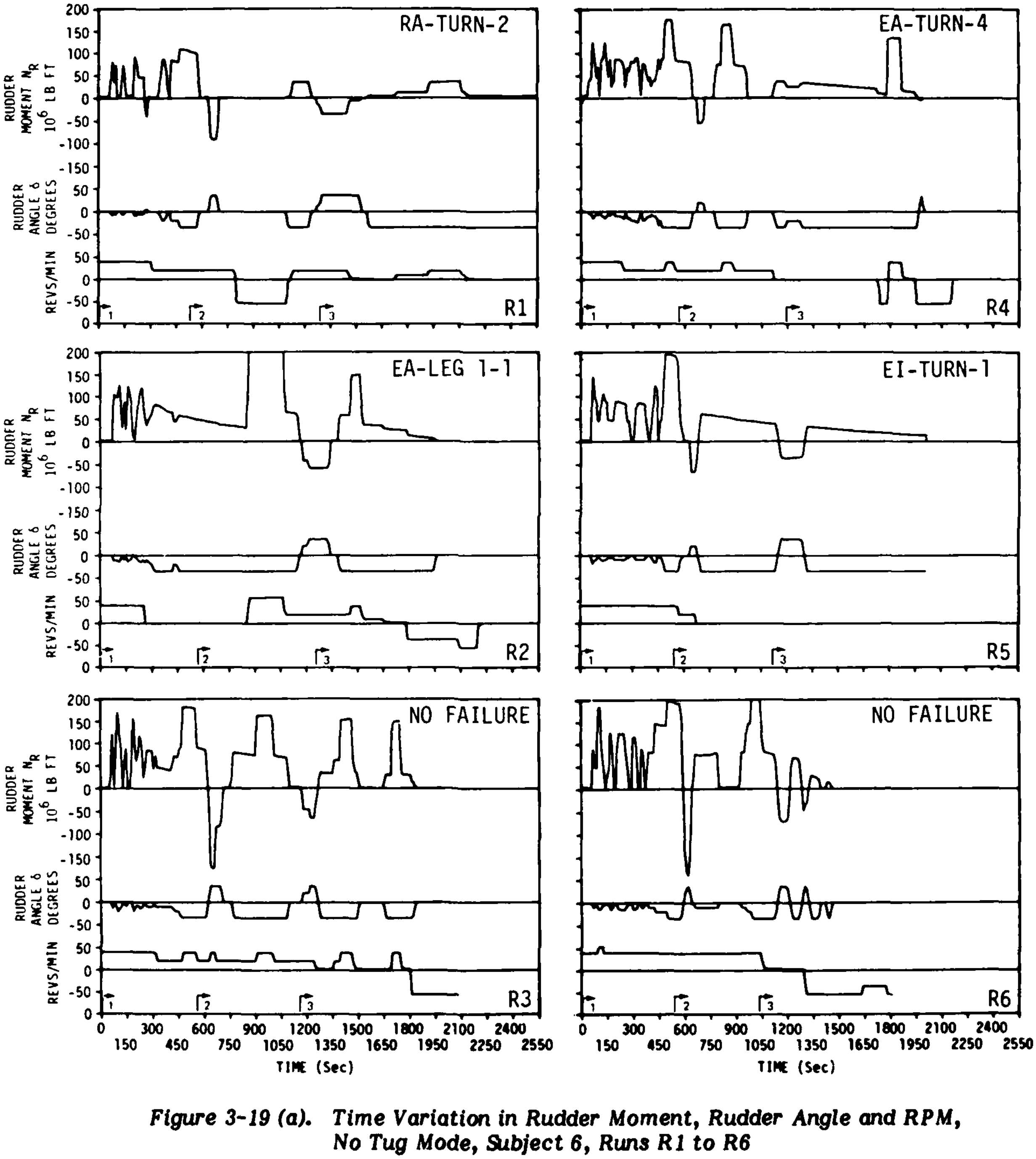


Figure 3-19 (a). Time Variation in Rudder Moment, Rudder Angle and RPM, No Tug Mode, Subject 6, Runs R1 to R6

SUBJECT 6 CONT

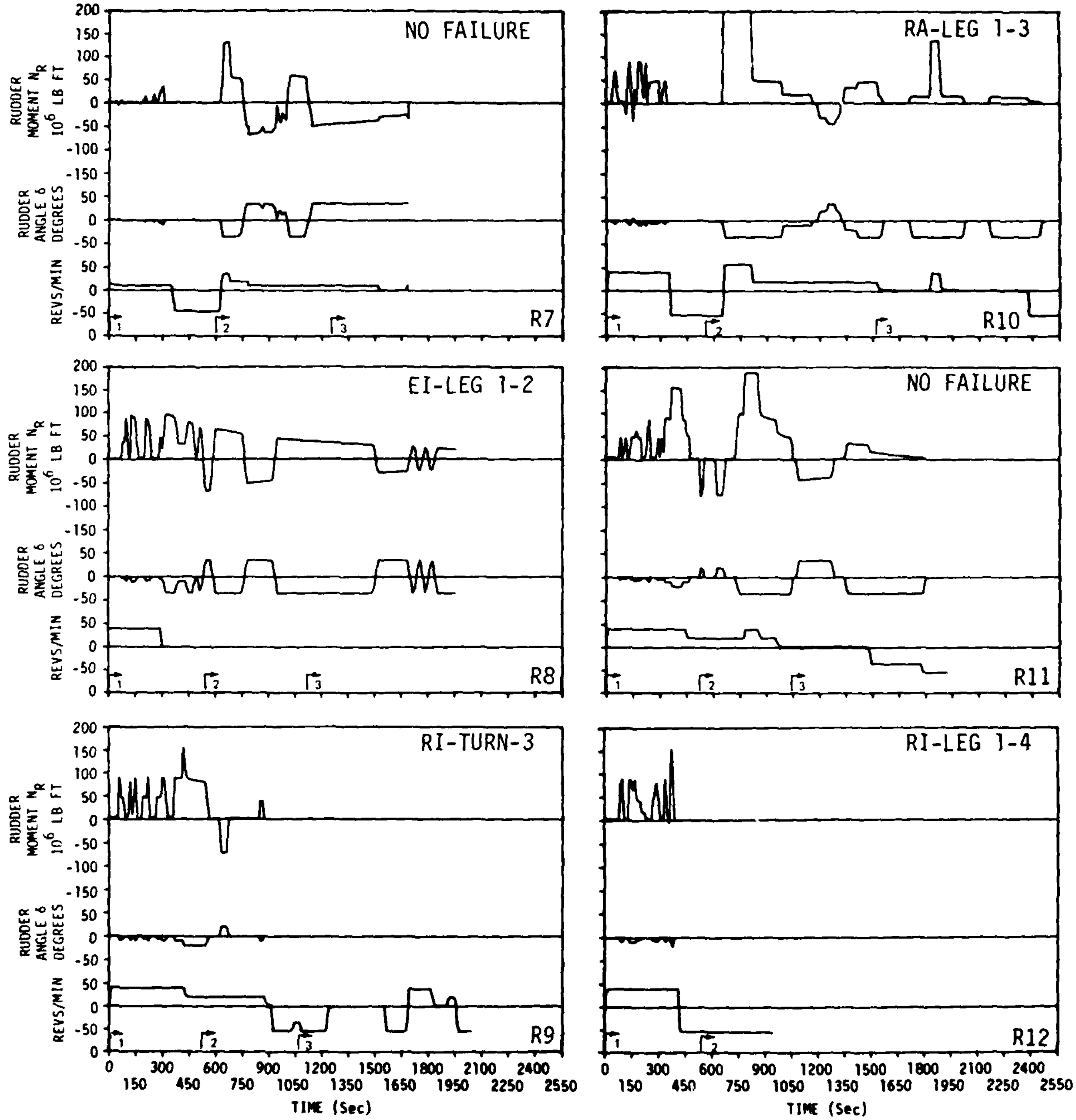


Figure 3-19 (b). Time Variation in Rudder Moment, Rudder Angle and RPM, No Tug Mode, Subject 6 (Cont), Runs R7 to R12

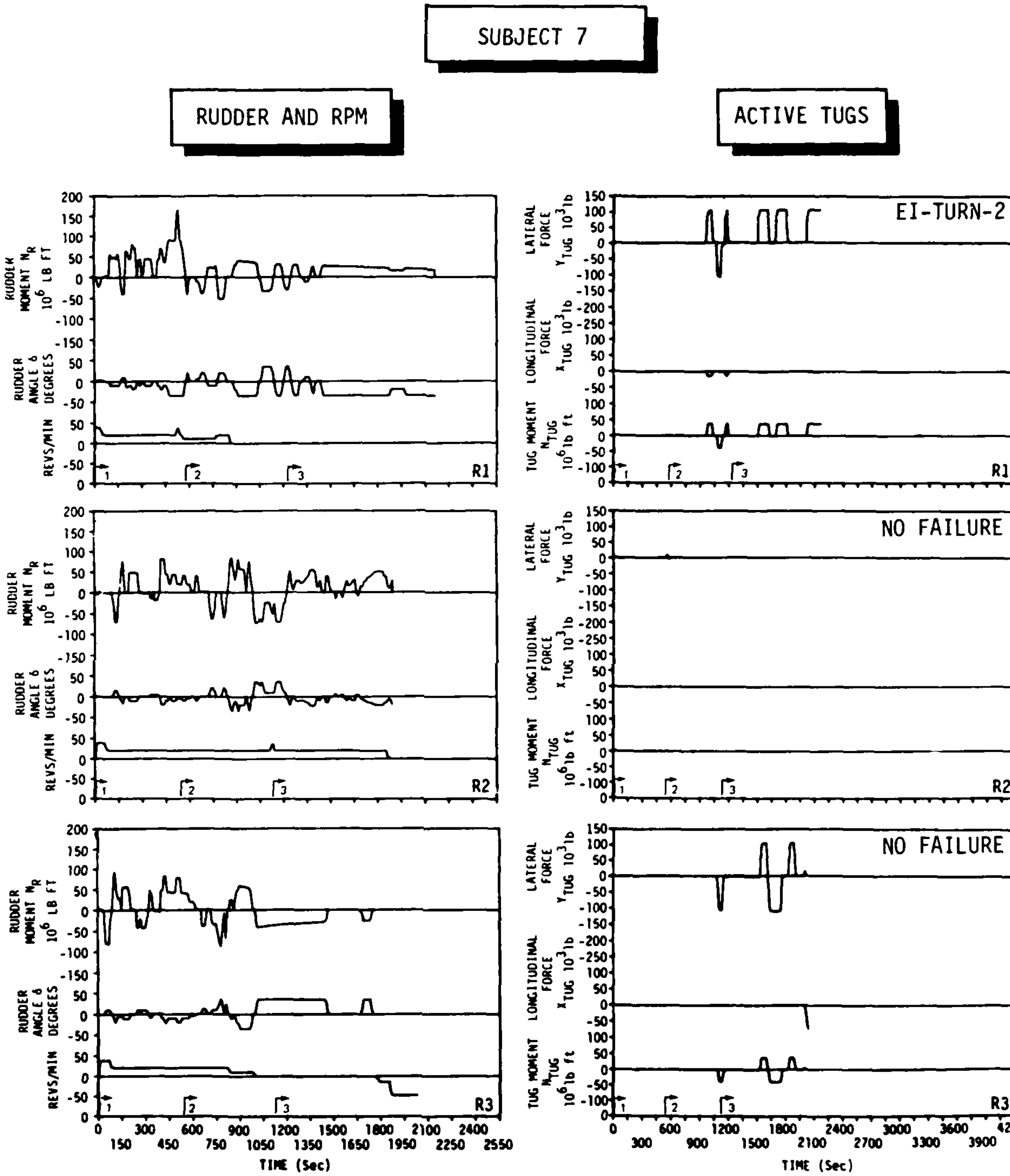


Figure 3-20 (a). Time Variation of Rudder Moment, Rudder Angle and RPM, Tug Forces and Moments, Active Tug Mode, Subject 7, Runs R1 to R3

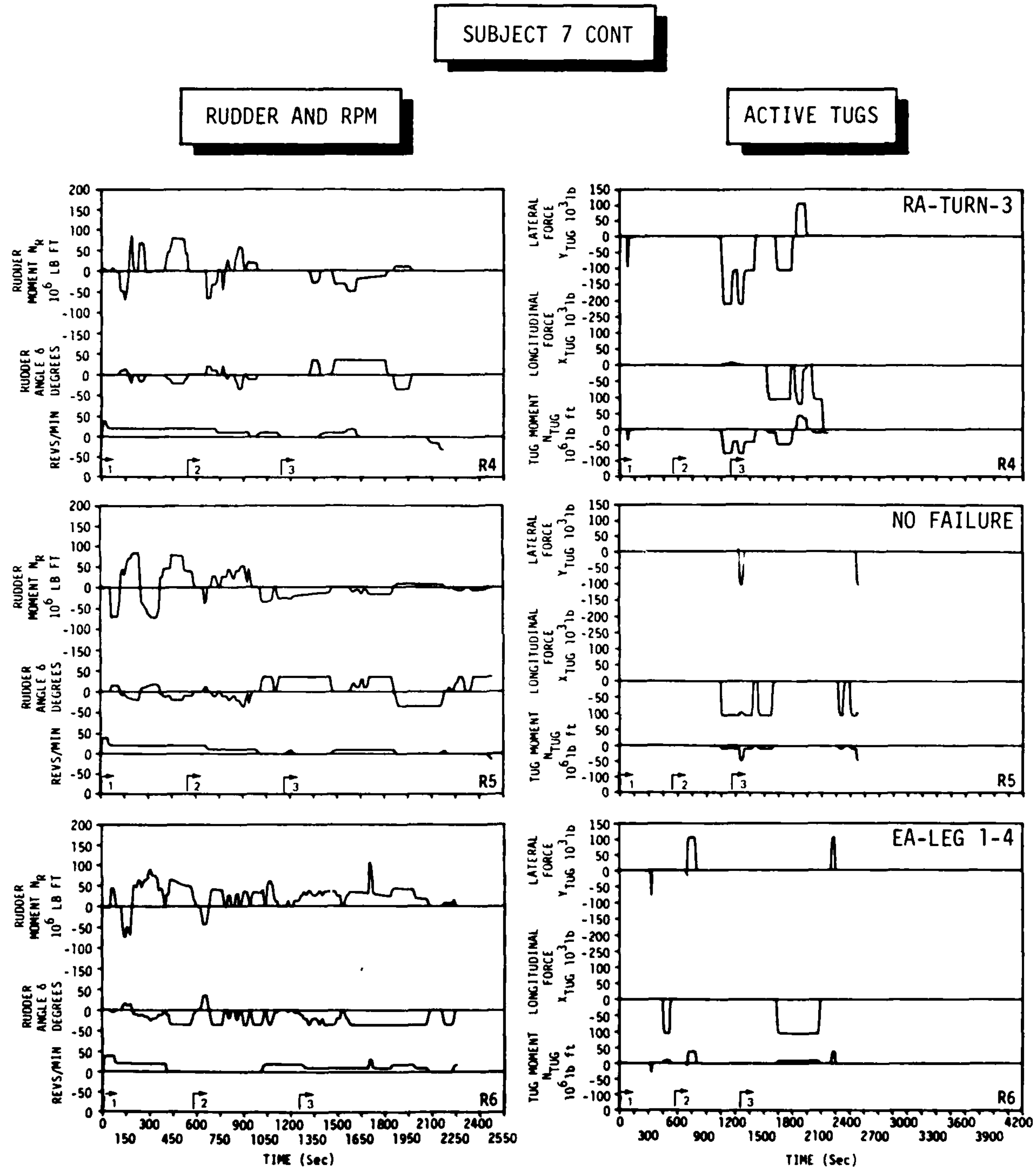


Figure 3-20 (b). Time Variation of Rudder Moment, Rudder Angle and RPM, Tug Forces and Moments, Active Tug Mode, Subject 7 (Cont), Run R4 to R6

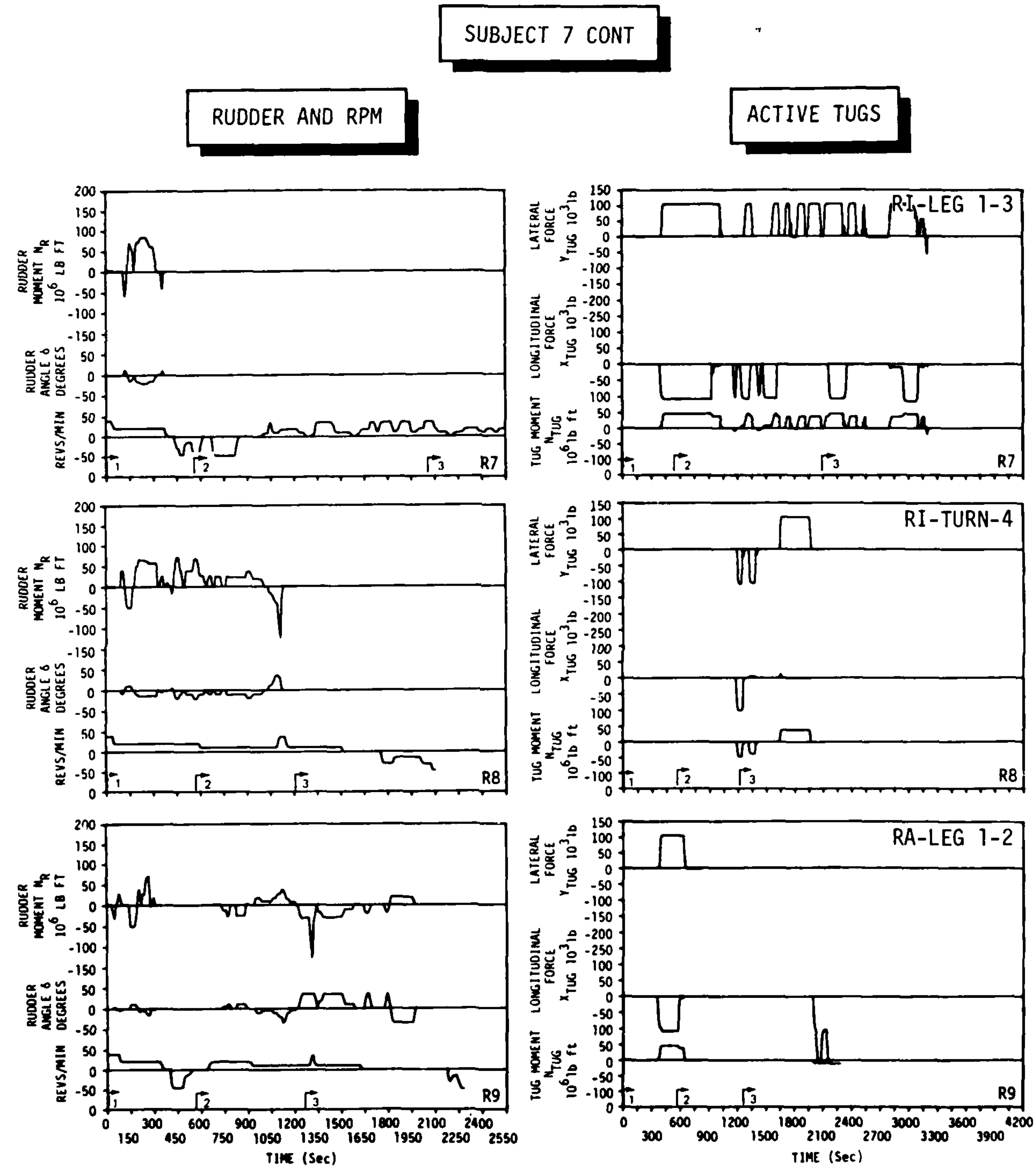


Figure 3-20 (c). Time Variation of Rudder Moment, Rudder Angle and RPM, Tug Forces and Moments, Active Tug Mode, Subject 7 (Cont), Runs R7 to R9

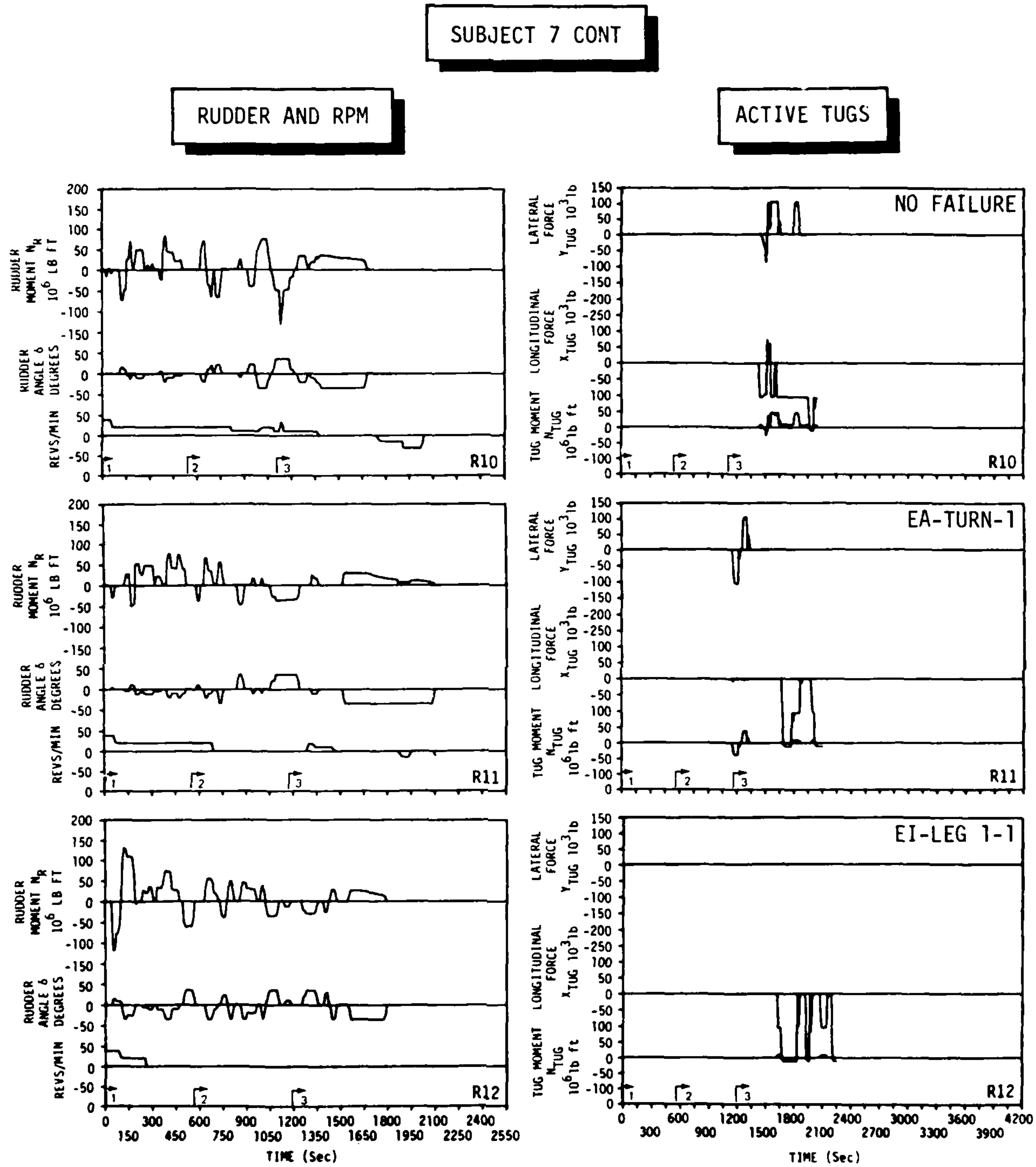


Figure 3-20 (d). Time Variation of Rudder Moment, Rudder Ange and RPM, Tug Forces and Moments, Active Tug Mode, Subject 7 (Cont), Runs R10 to R12

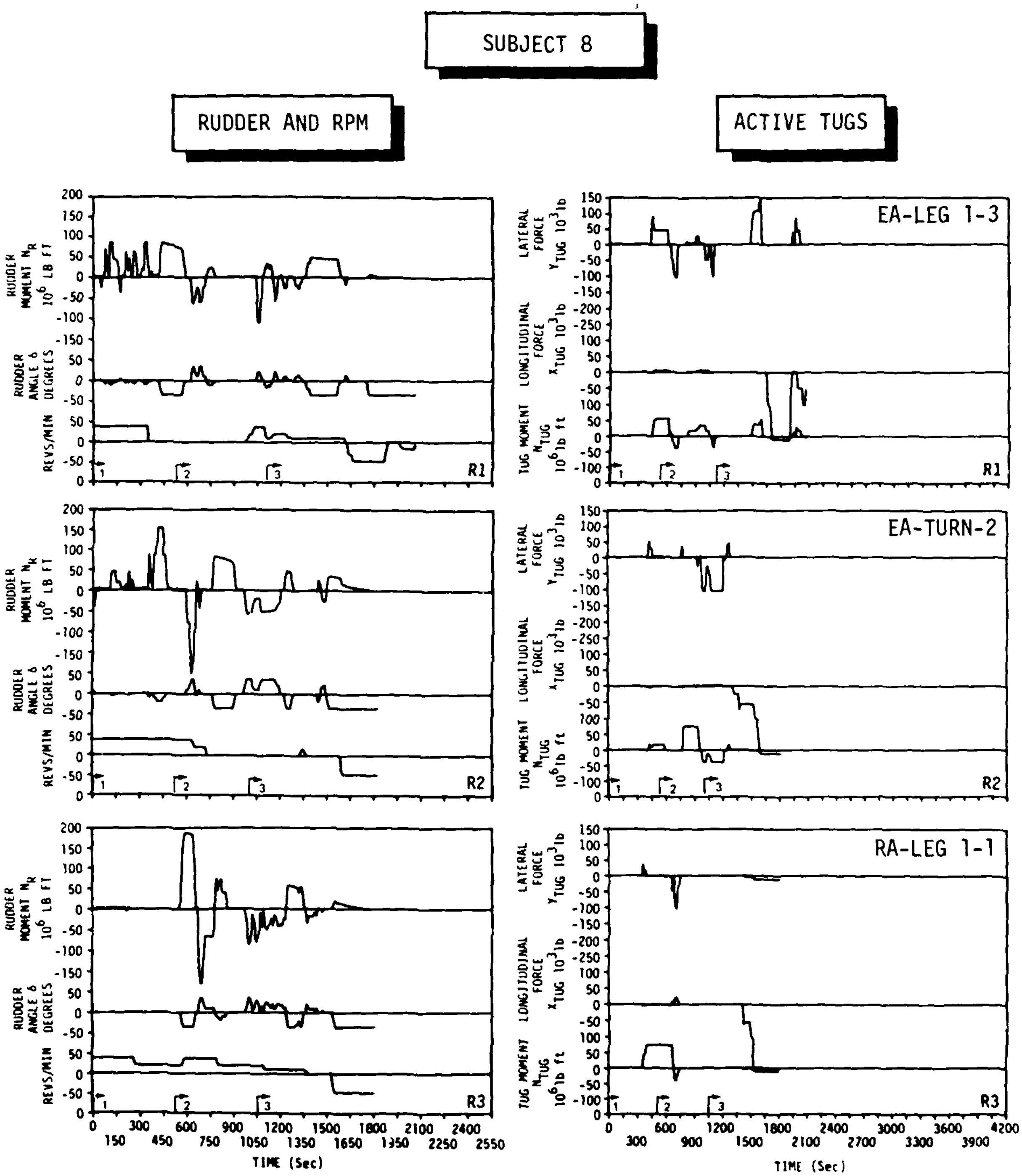


Figure 3-21 (a). Time Variation of Rudder Moment, Rudder Angle and RPM, Tug Forces and Moments, Active Tug Mode, Subject 8, Runs R1 to R3

SUBJECT 8 CONT

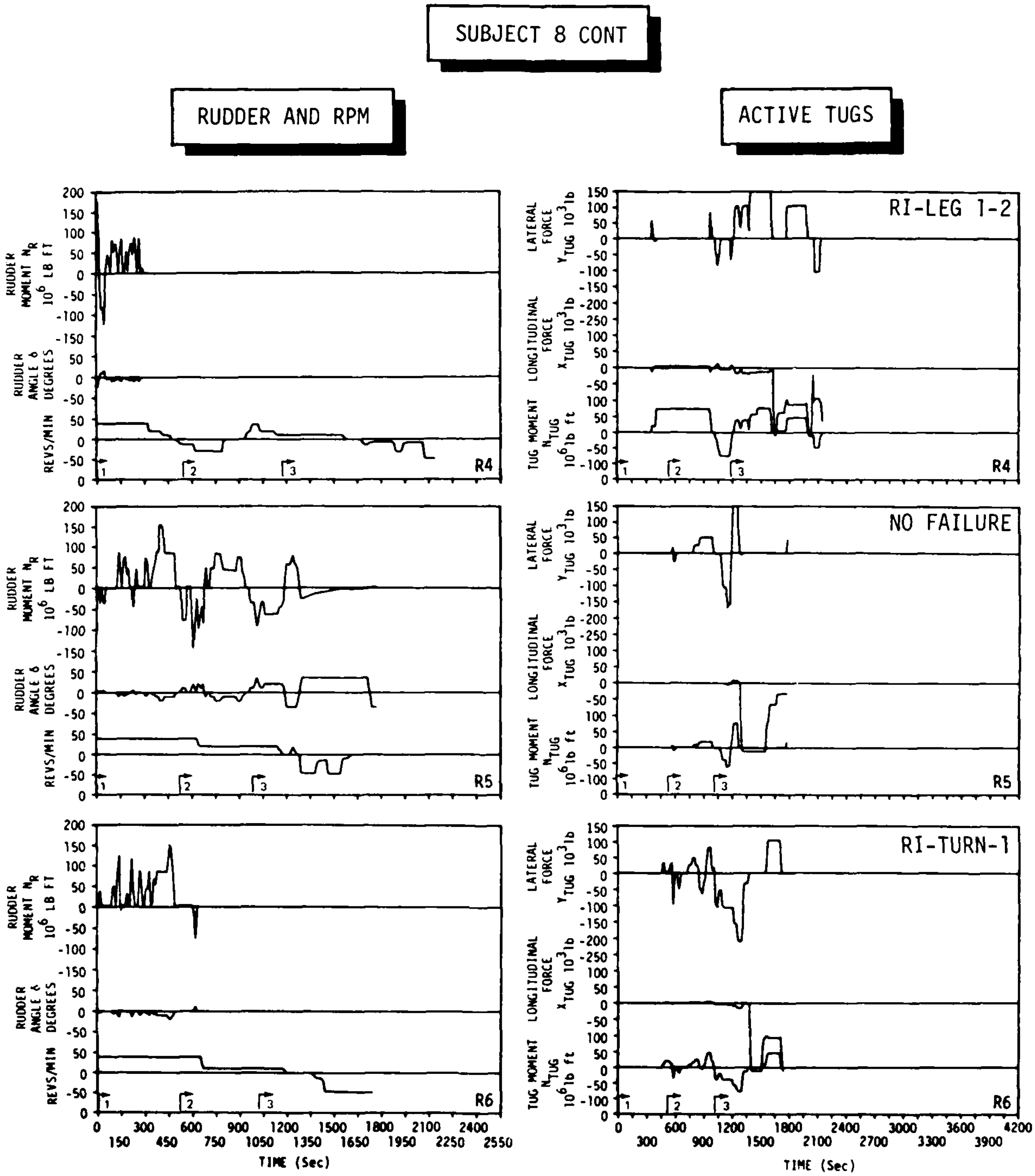


Figure 3-21 (b). Time Variation of Rudder Moment, Rudder Angle and RPM, Tug Forces and Moments, Active Tug Mode, Subject 8 (Cont), Run R4 to R6

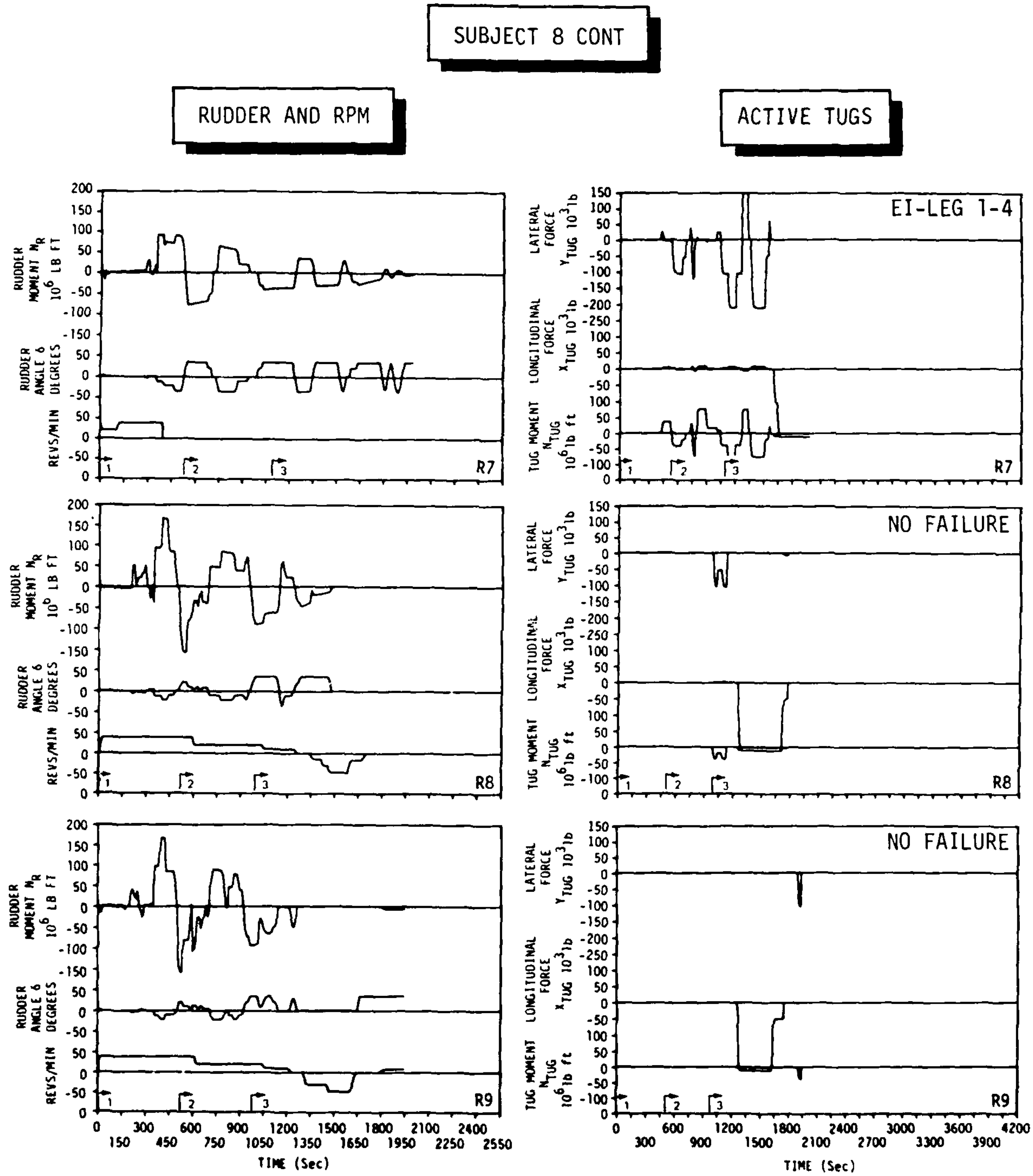


Figure 3-21 (c). Time Variation of Rudder Moment, Rudder Angle and RPM, Tug Forces and Moments, Active Tug Mode, Subject 8 (Cont), Runs R7 to R9

SUBJECT 8 CONT

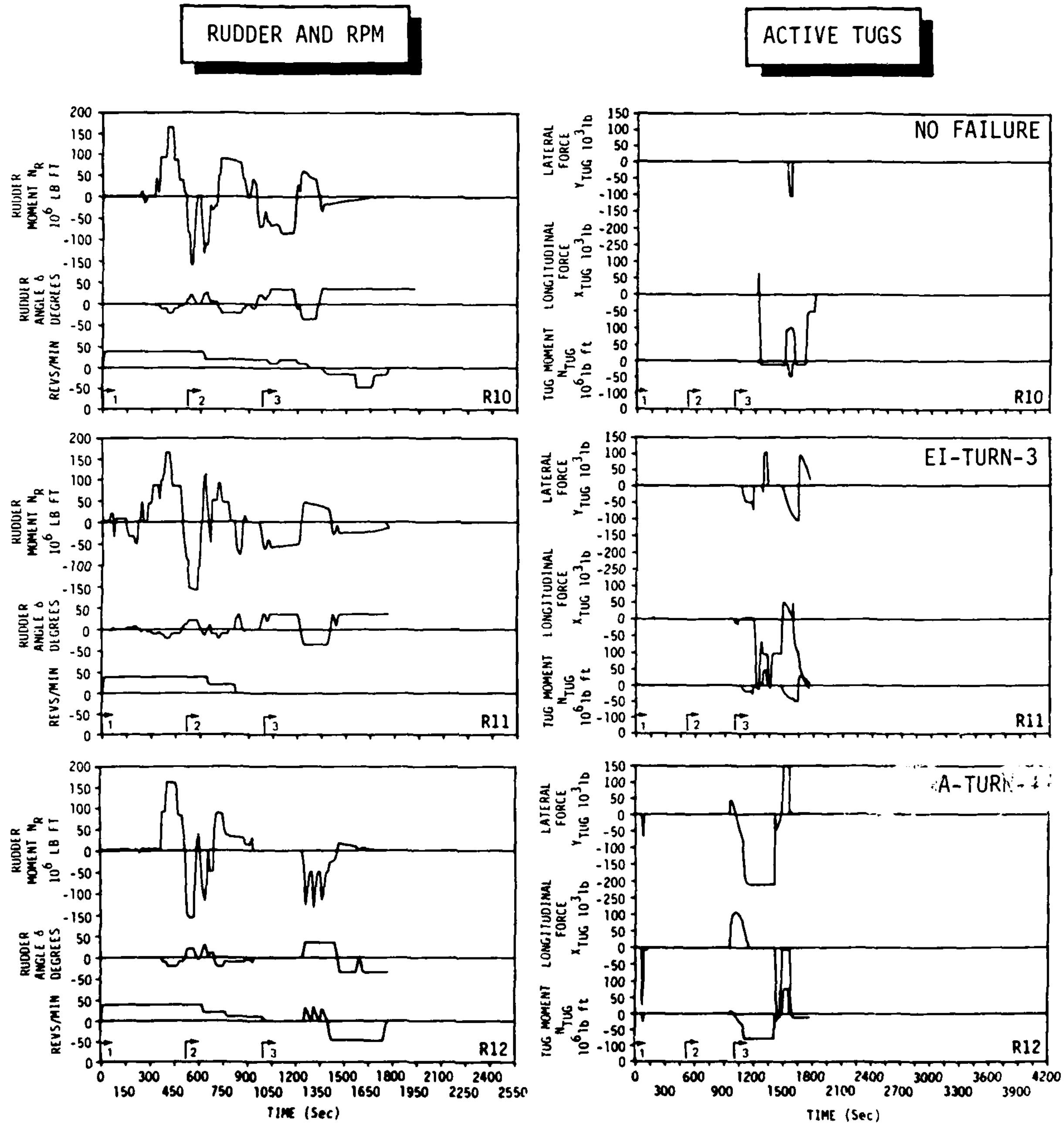


Figure 3-21 (d). Time Variation of Rudder Moment, Rudder Ange and RPM, Tug Forces and Moments, Active Tug Mode, Subject 8 (Cont), Runs R10 to R12

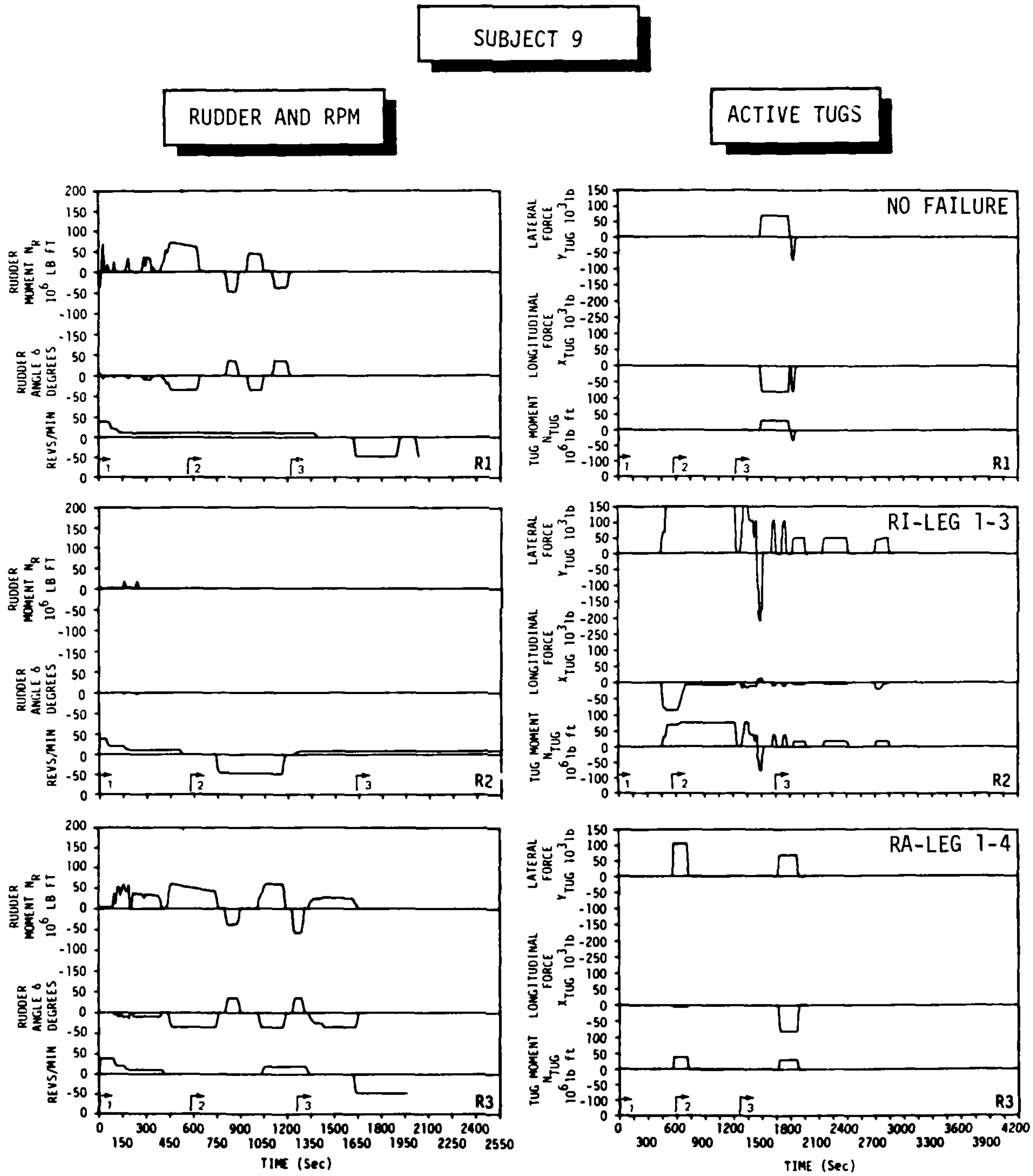


Figure 3-22 (a). Time Variation of Rudder Moment, Rudder Angle and RPM, Tug Forces and Moments, Active Tug Mode, Subject 9, Runs R1 to R3

SUBJECT 9 CONT

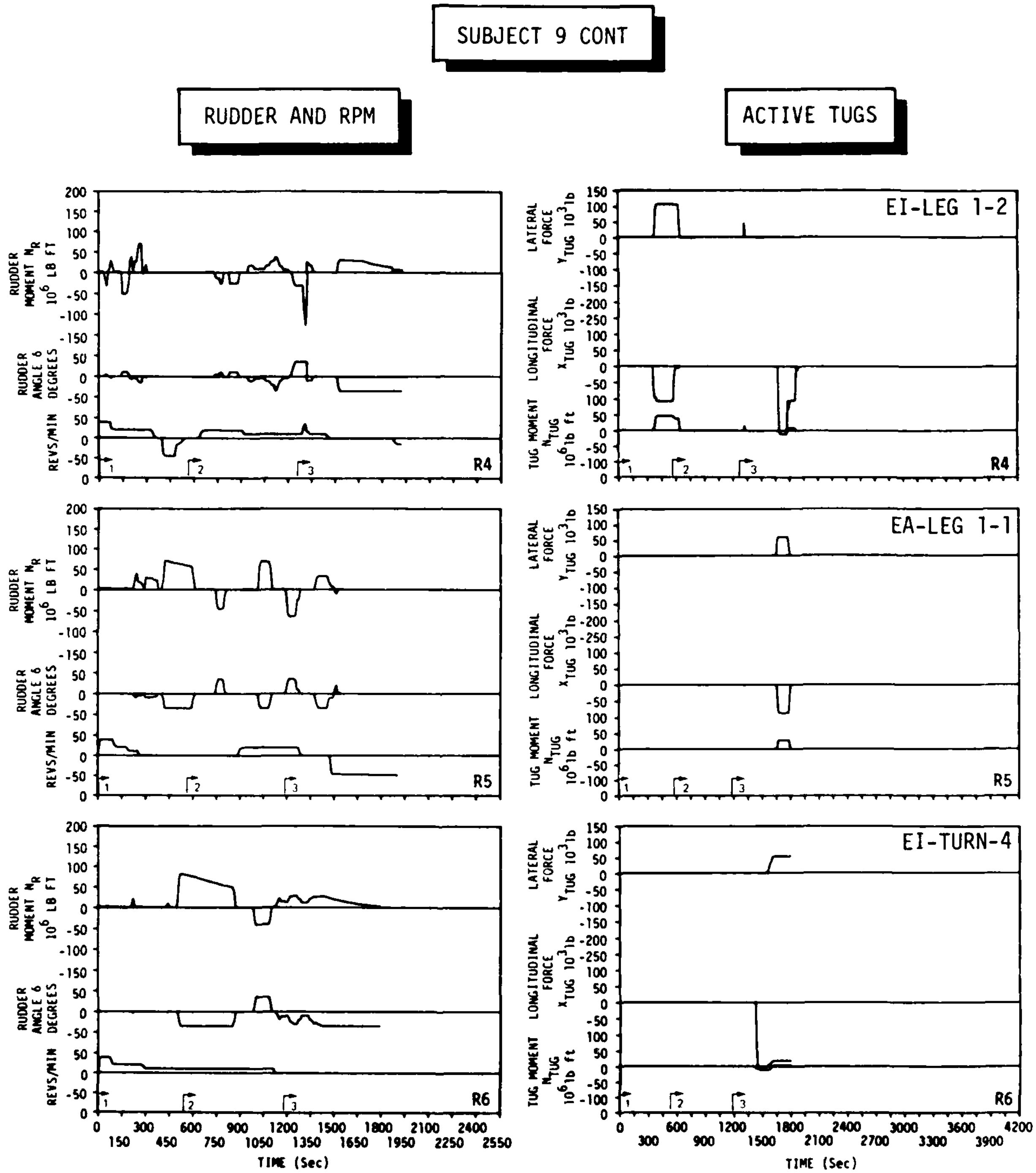


Figure 3-22 (b). Time Variation of Rudder Moment, Rudder Angle and RPM, Tug Forces and Moments, Active Tug Mode, Subject 9 (Cont), Run R4 to R6

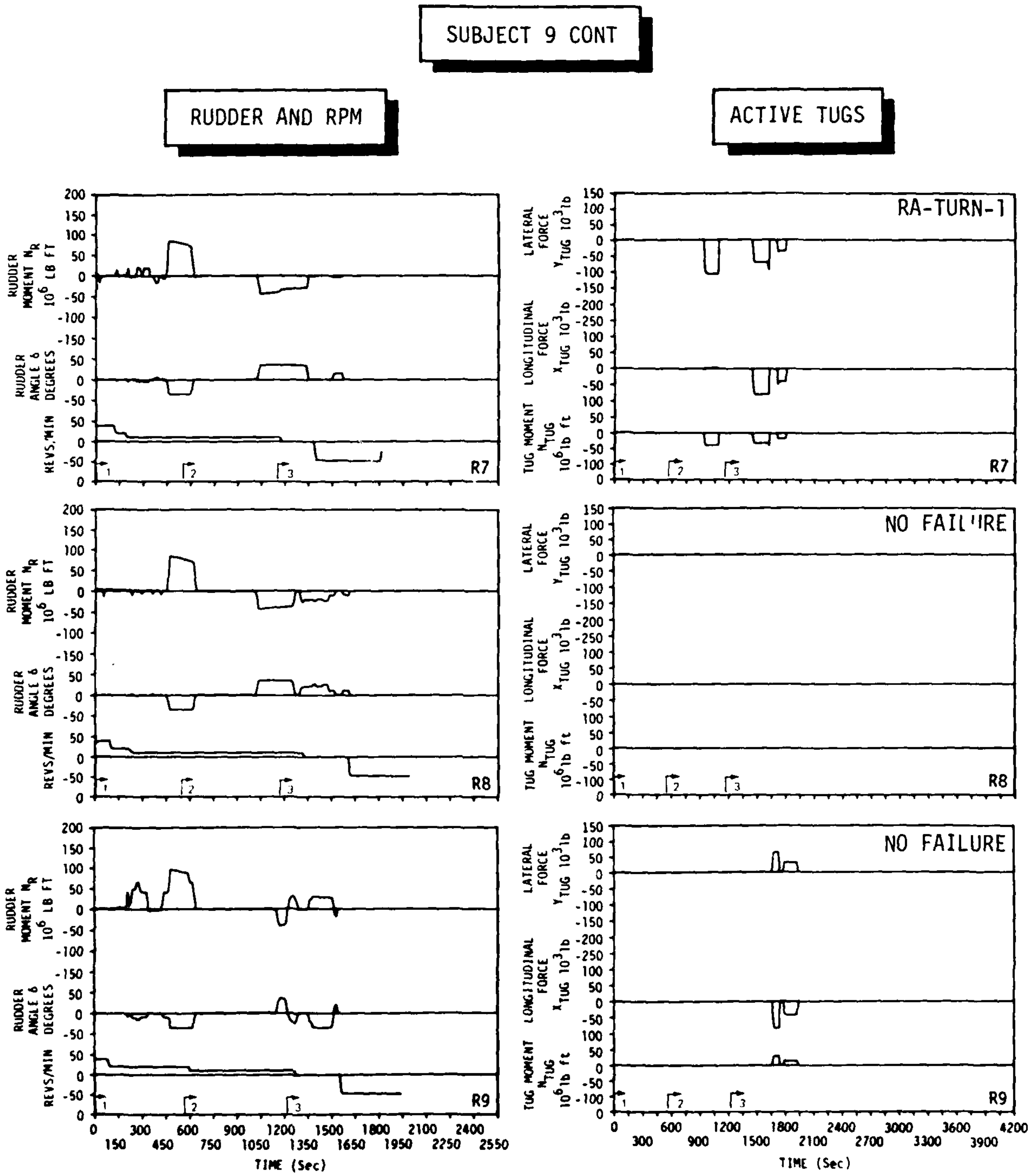


Figure 3-22 (c). Time Variation of Rudder Moment, Rudder Angle and RPM, Tug Forces and Moments, Active Tug Mode, Subject 9 (Cont), Runs R7 to R9

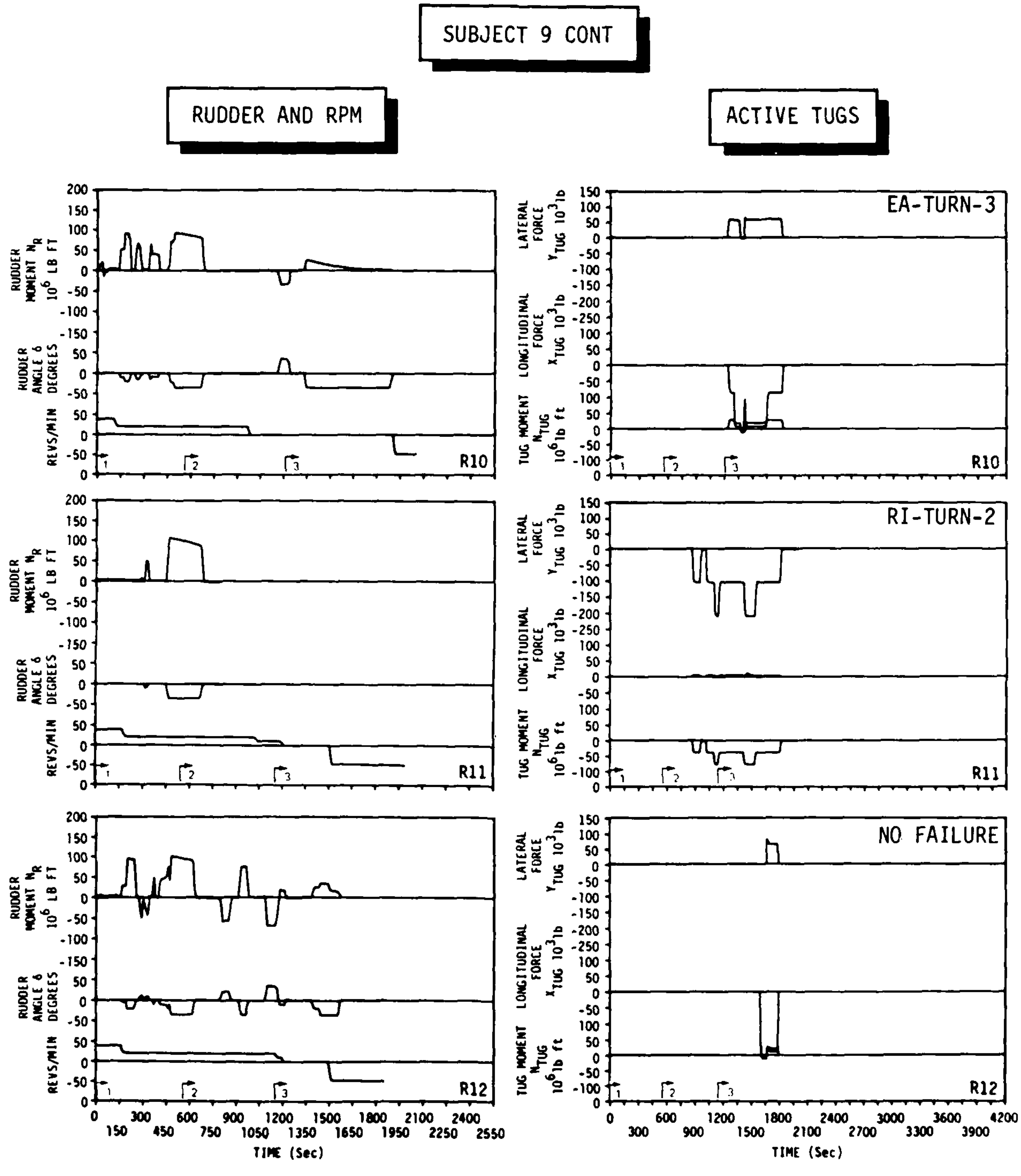


Figure 3-22 (d). Time Variation of Rudder Moment, Rudder Ange and RPM, Tug Forces and Moments, Active Tug Mode, Subject 9 (Cont), Runs R10 to R12

SUBJECT 10

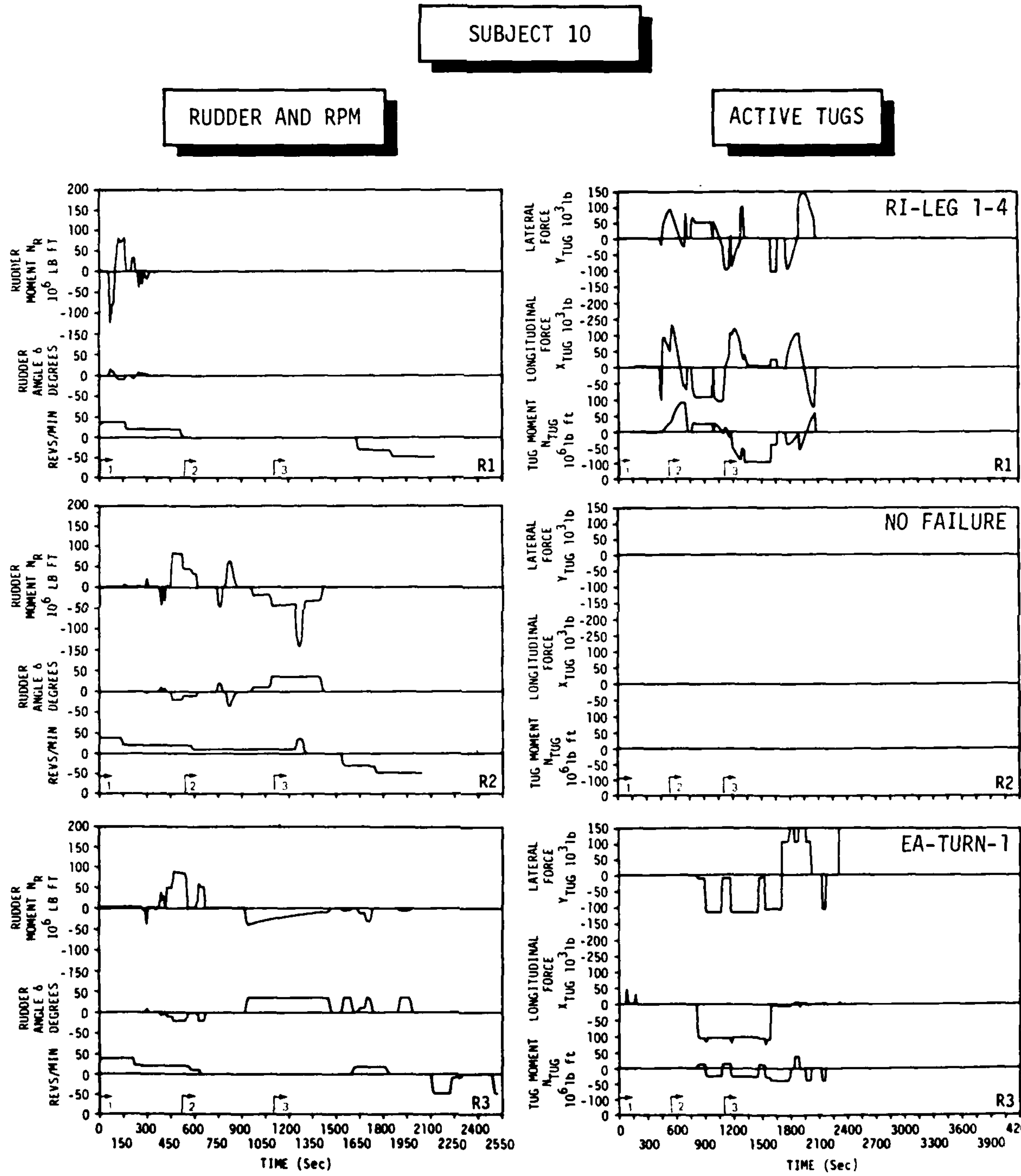


Figure 3-23 (a). Time Variation of Rudder Moment, Rudder Angle and RPM, Tug Forces and Moments, Active Tug Mode, Subject 10, Runs R1 to R3

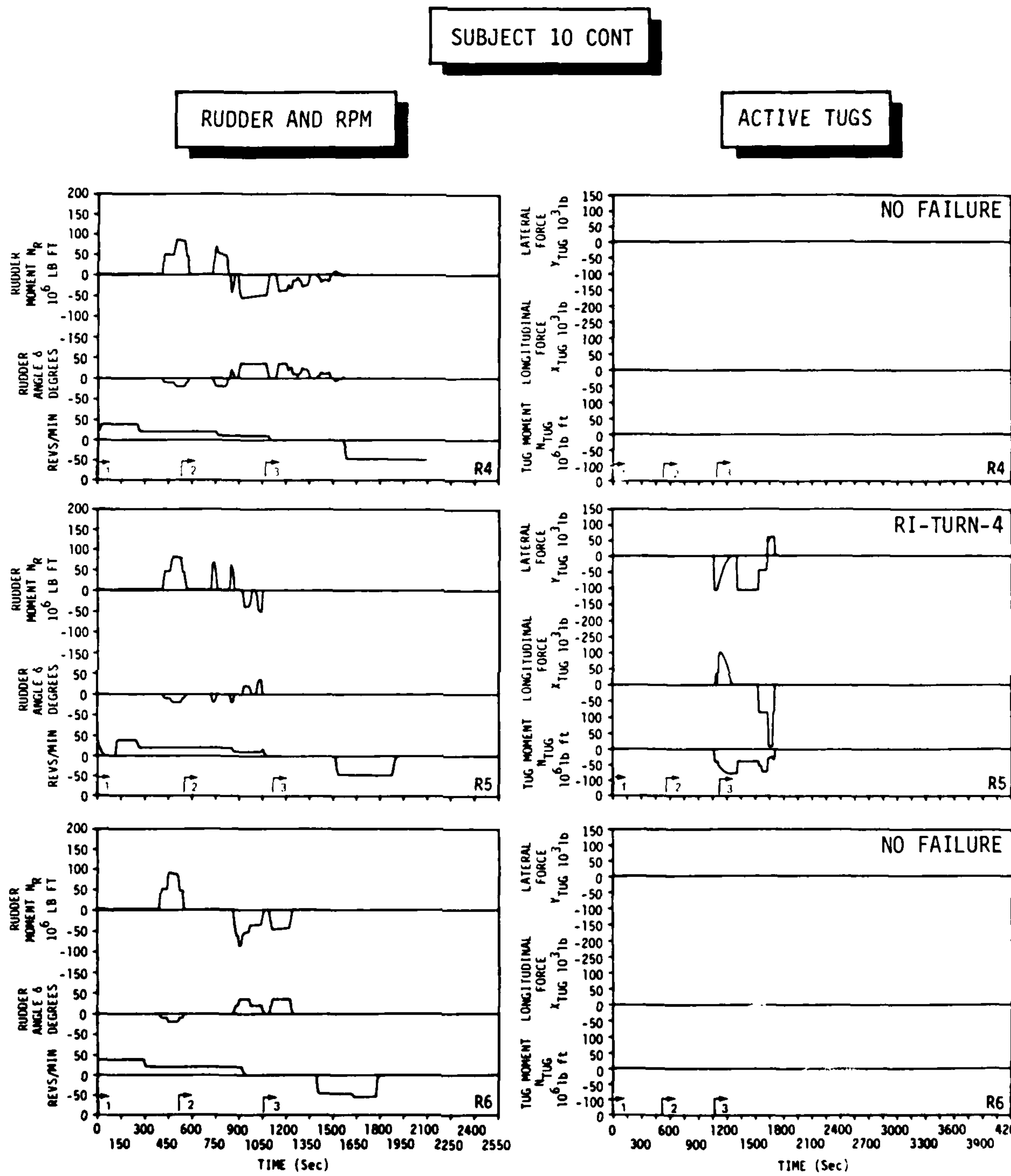


Figure 3-23 (b). Time Variation of Rudder Moment, Rudder Angle and RPM, Tug Forces and Moments, Active Tug Mode, Subject 10 (Cont), Run R4 to R6

SUBJECT 10 CONT

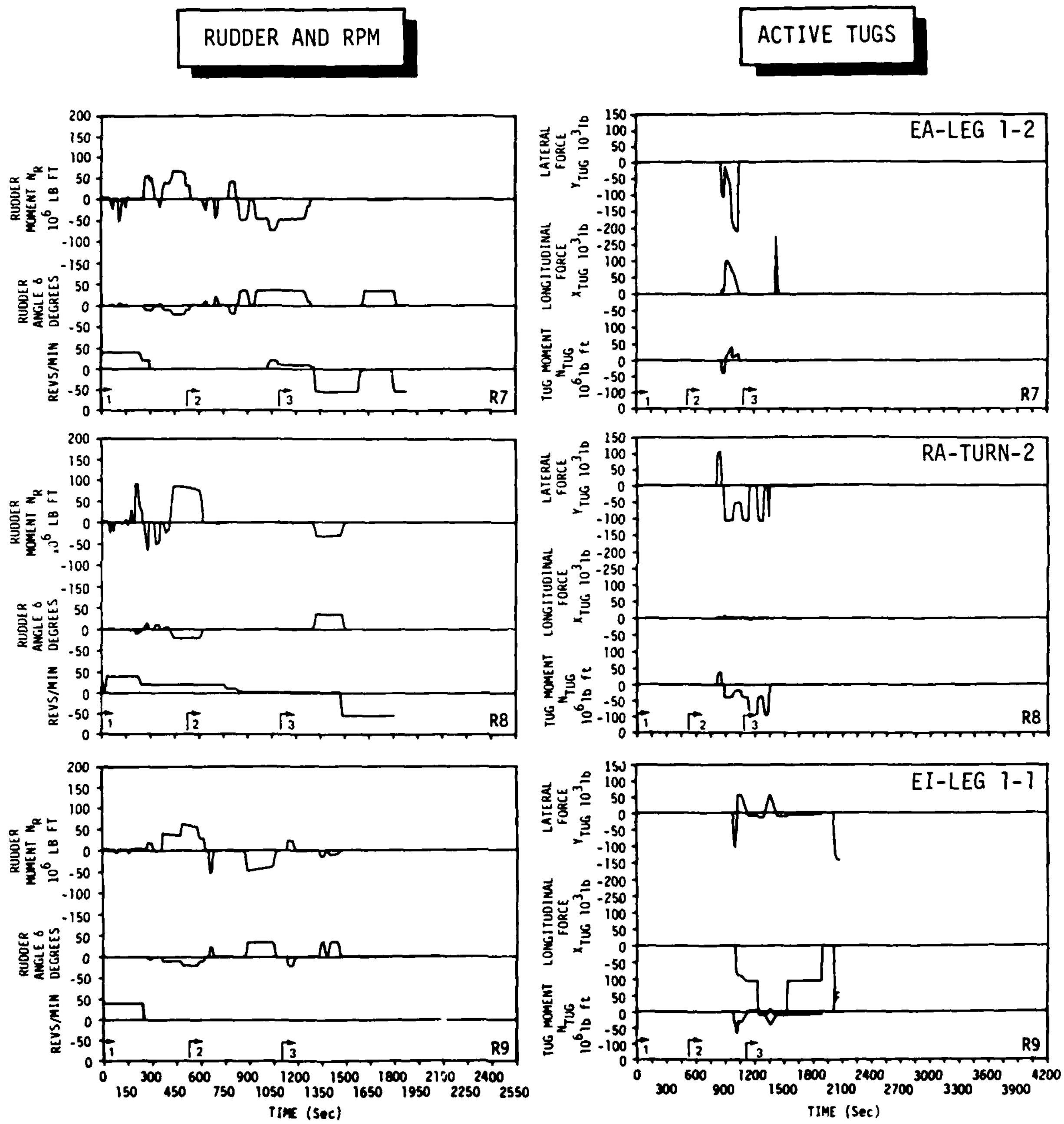


Figure 3-23 (c). Time Variation of Rudder Moment, Rudder Angle and RPM, Tug Forces and Moments, Active Tug Mode, Subject 10 (Cont), Runs R7 to R9

SUBJECT 10 CONT

RUDDER AND RPM

ACTIVE TUGS

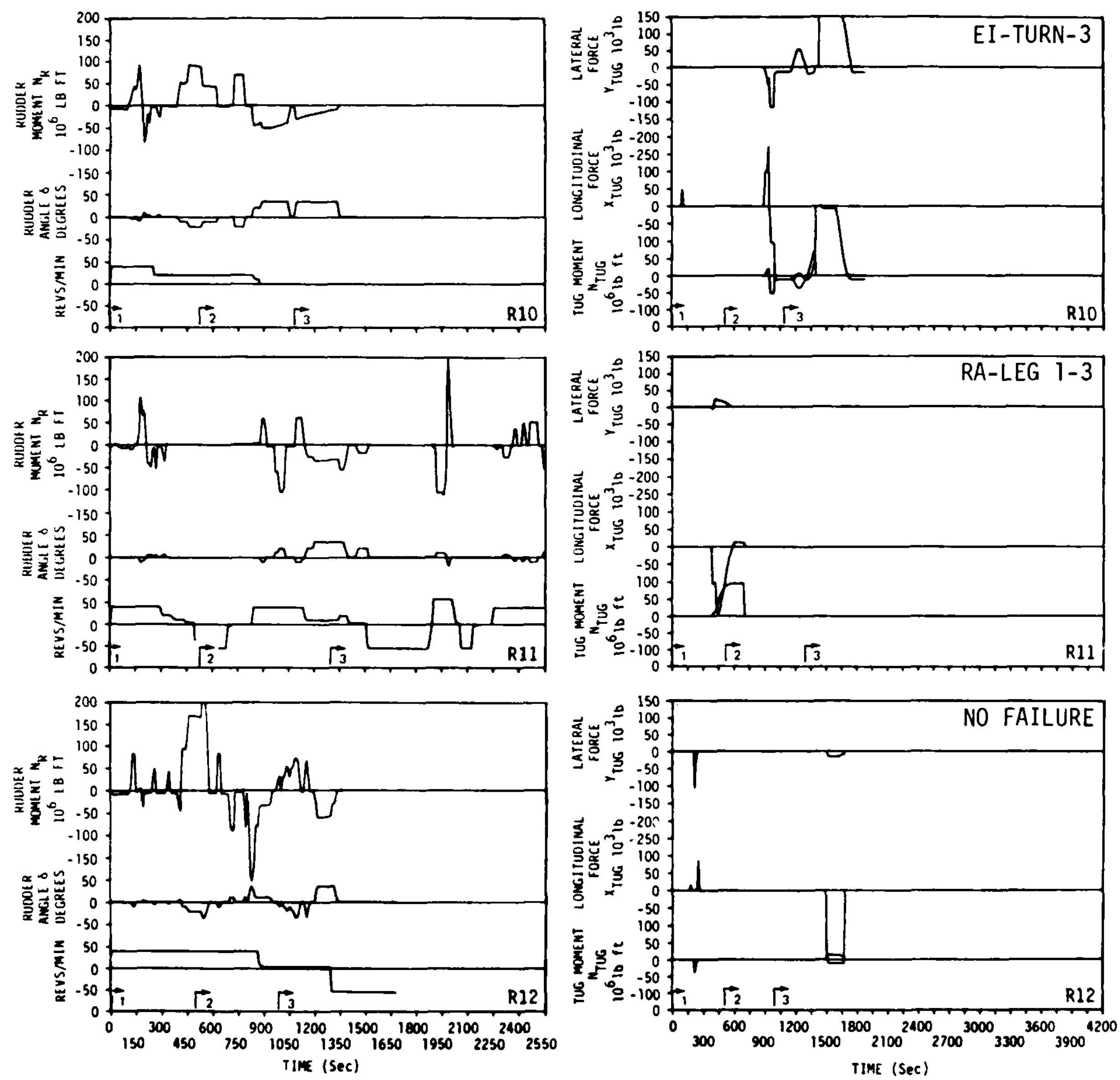


Figure 3-23 (d). Time Variation of Rudder Moment, Rudder Ange and RPM, Tug Forces and Moments, Active Tug Mode, Subject 10 (Cont), Runs R10 to R12

SUBJECT 11

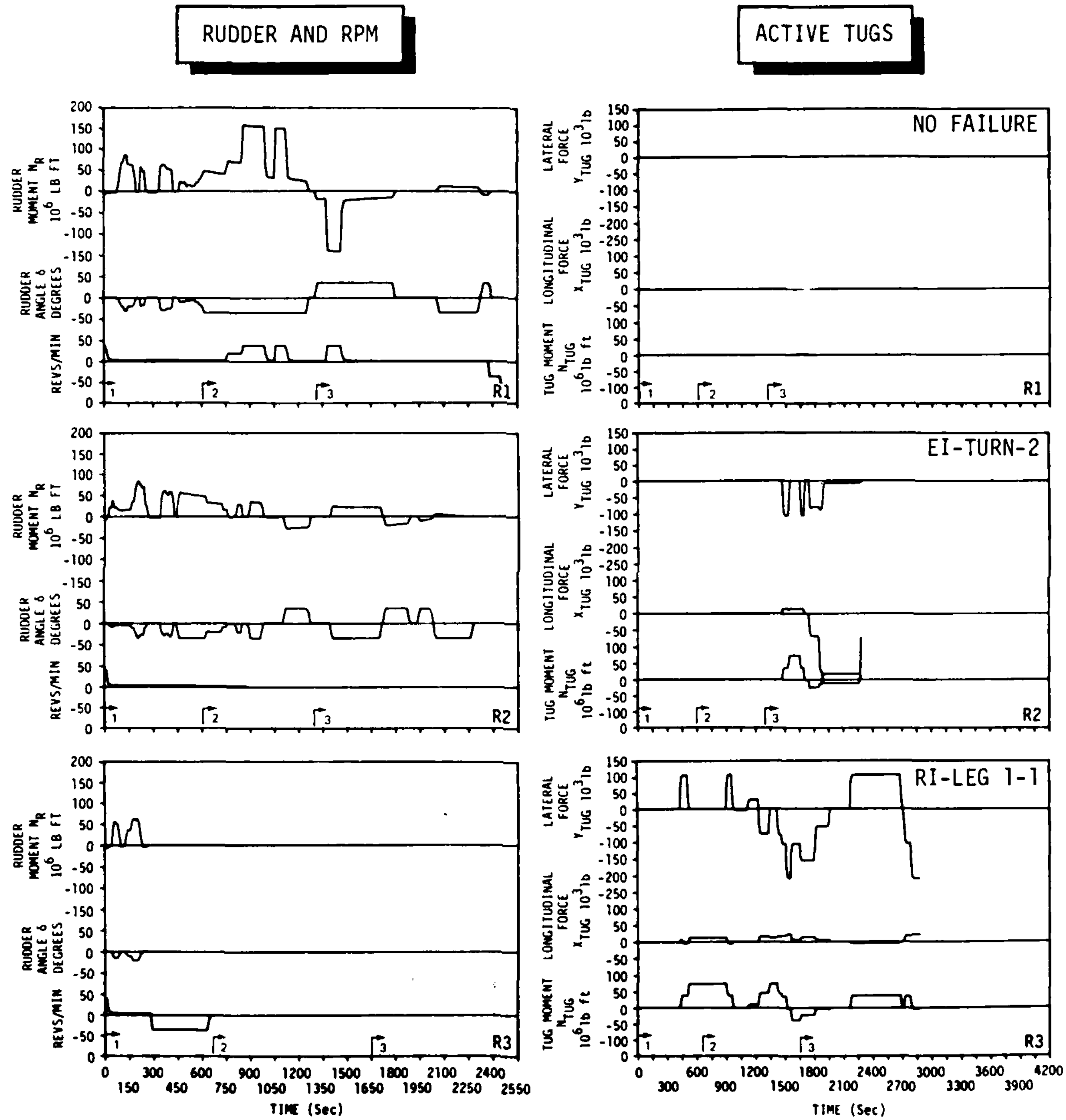


Figure 3-24 (a). Time Variation of Rudder Moment, Rudder Angle and RPM, Tug Forces and Moments, Active Tug Mode, Subject 11, Runs R1 to R3

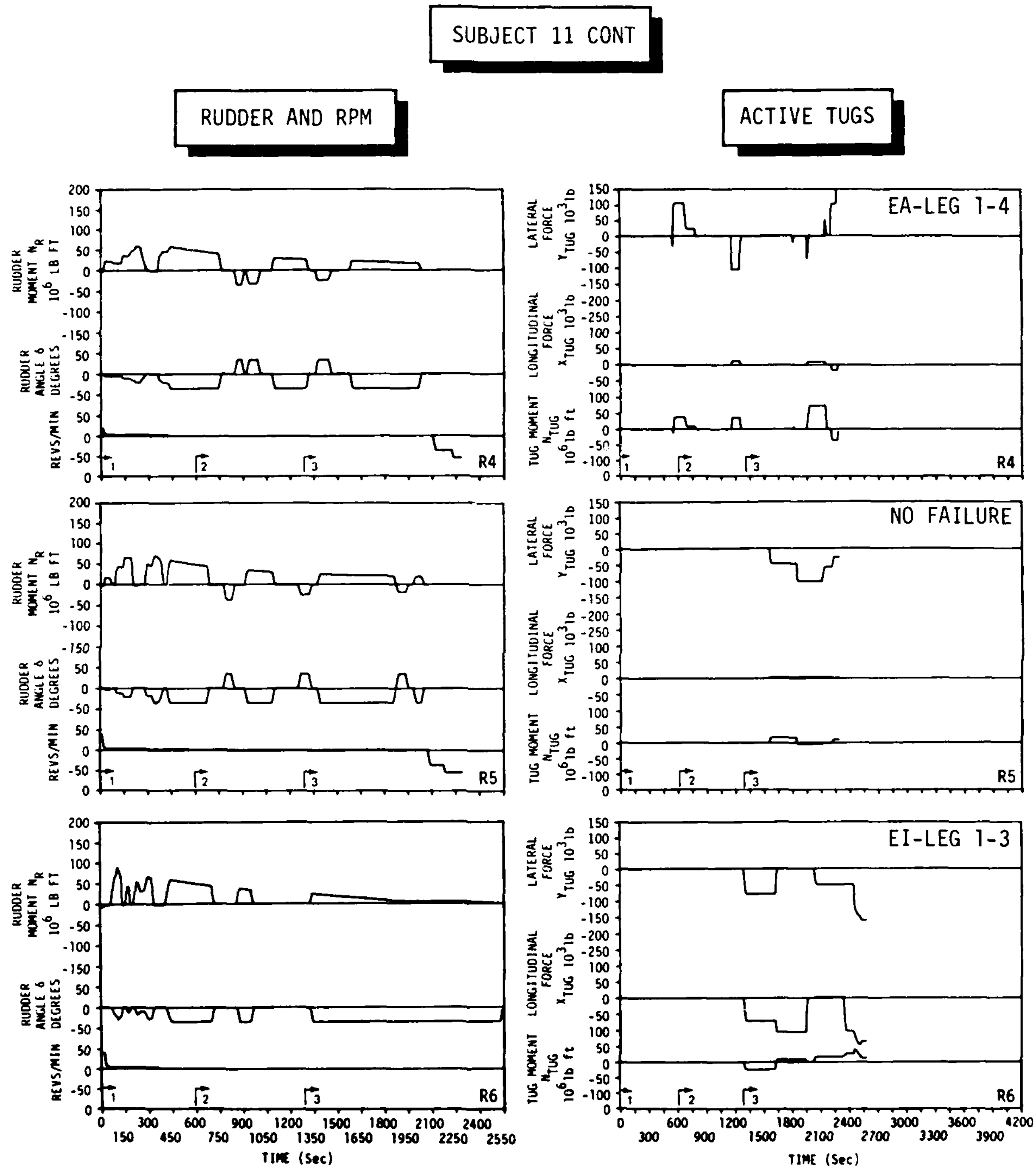


Figure 3-24 (b). Time Variation of Rudder Moment, Rudder Angle and RPM, Tug Forces and Moments, Active Tug Mode, Subject 11 (Cont), Run R4 to R6

SUBJECT 11 CONT

RUDDER AND RPM

ACTIVE TUGS

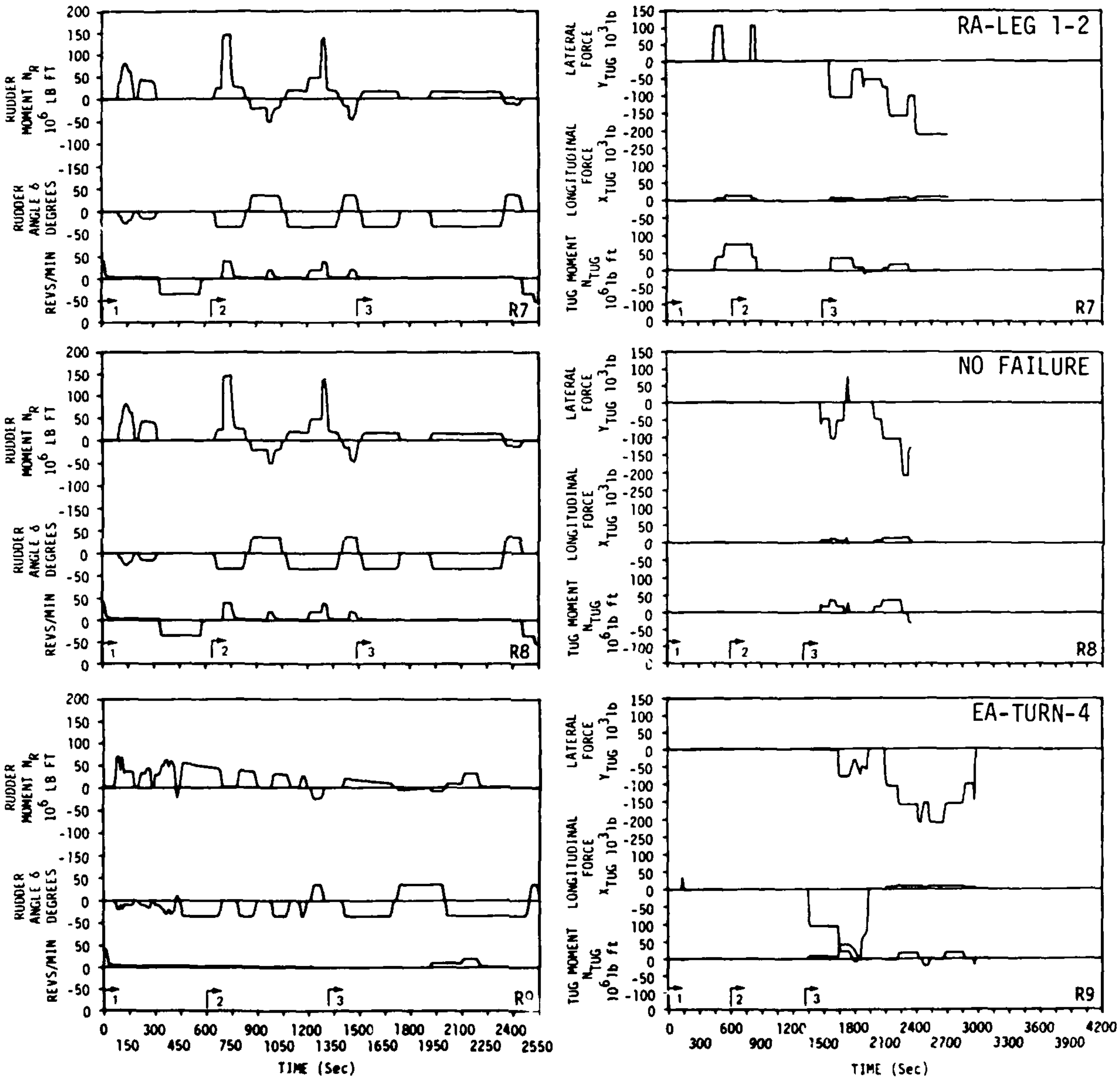


Figure 3-24 (c). Time Variation of Rudder Moment, Rudder Angle and RPM, Tug Forces and Moments, Active Tug Mode, Subject 11 (Cont), Runs R7 to R9

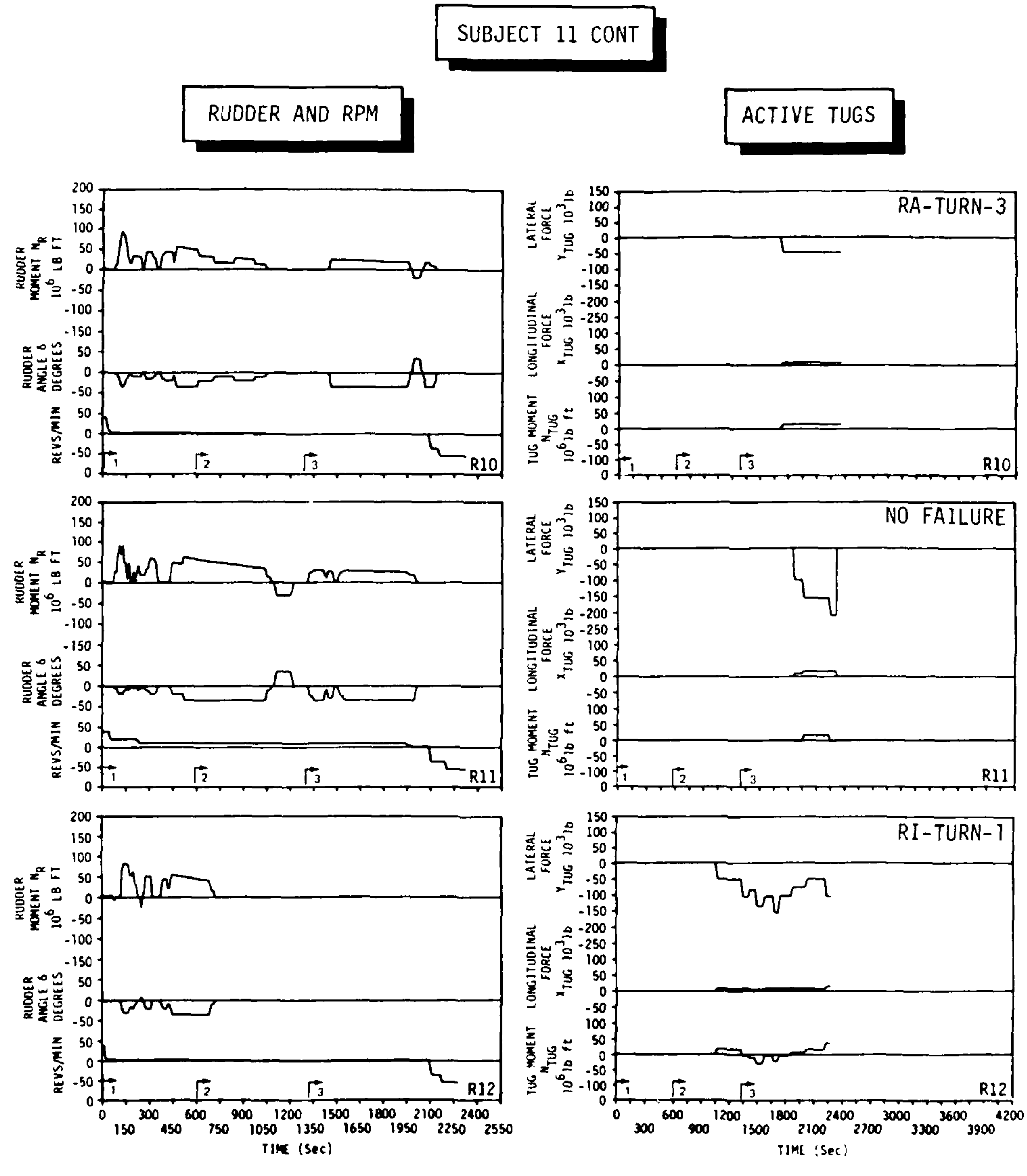


Figure 3-24 (d). Time Variation of Rudder Moment, Rudder Ange and RPM, Tug Forces and Moments, Active Tug Mode, Subject 11 (Cont), Runs R10 to R12

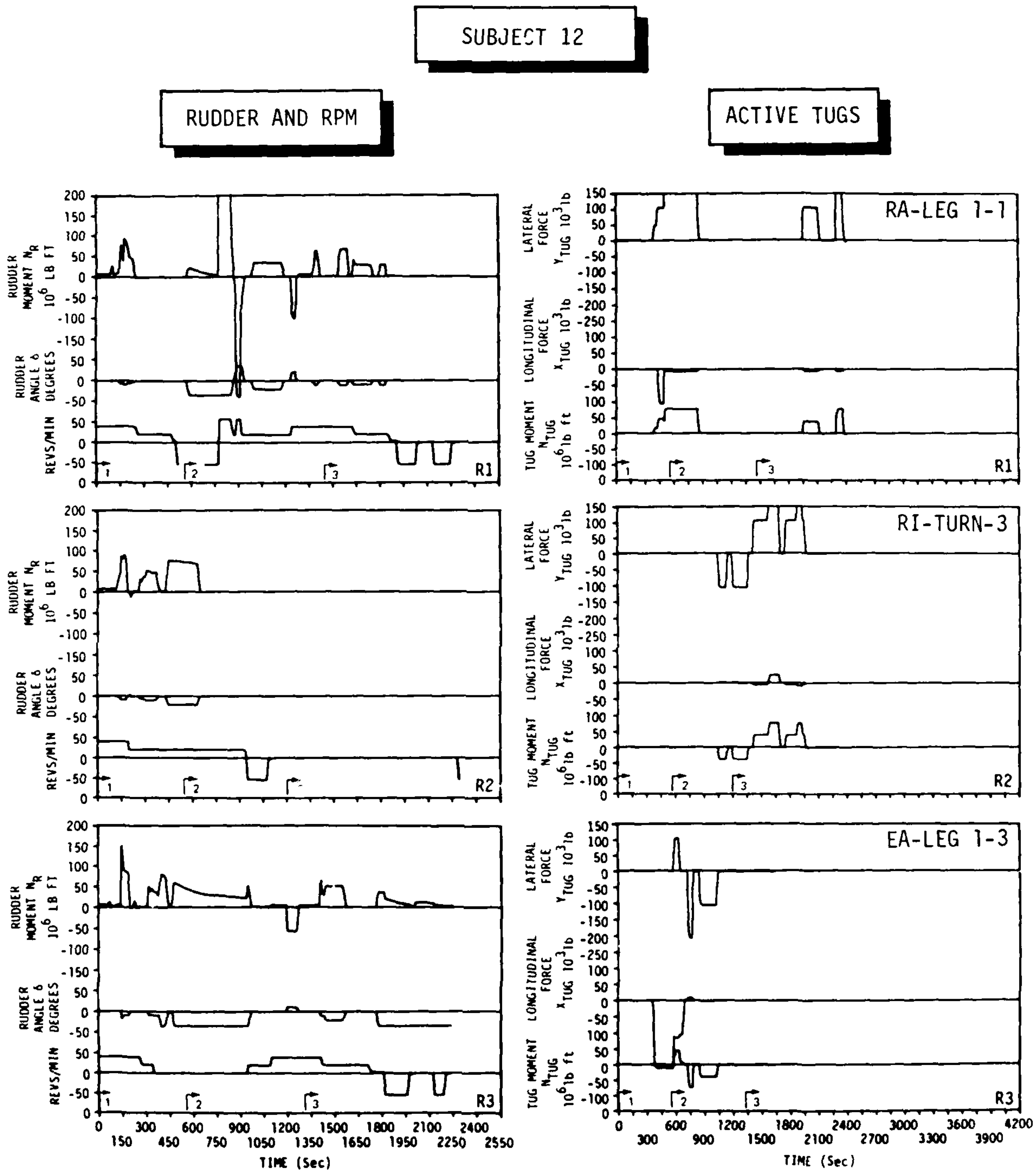


Figure 3-25 (a). Time Variation of Rudder Moment, Rudder Angle and RPM, Tug Forces and Moments, Active Tug Mode, Subject 12, Runs R1 to R3

SUBJECT 12 CONT

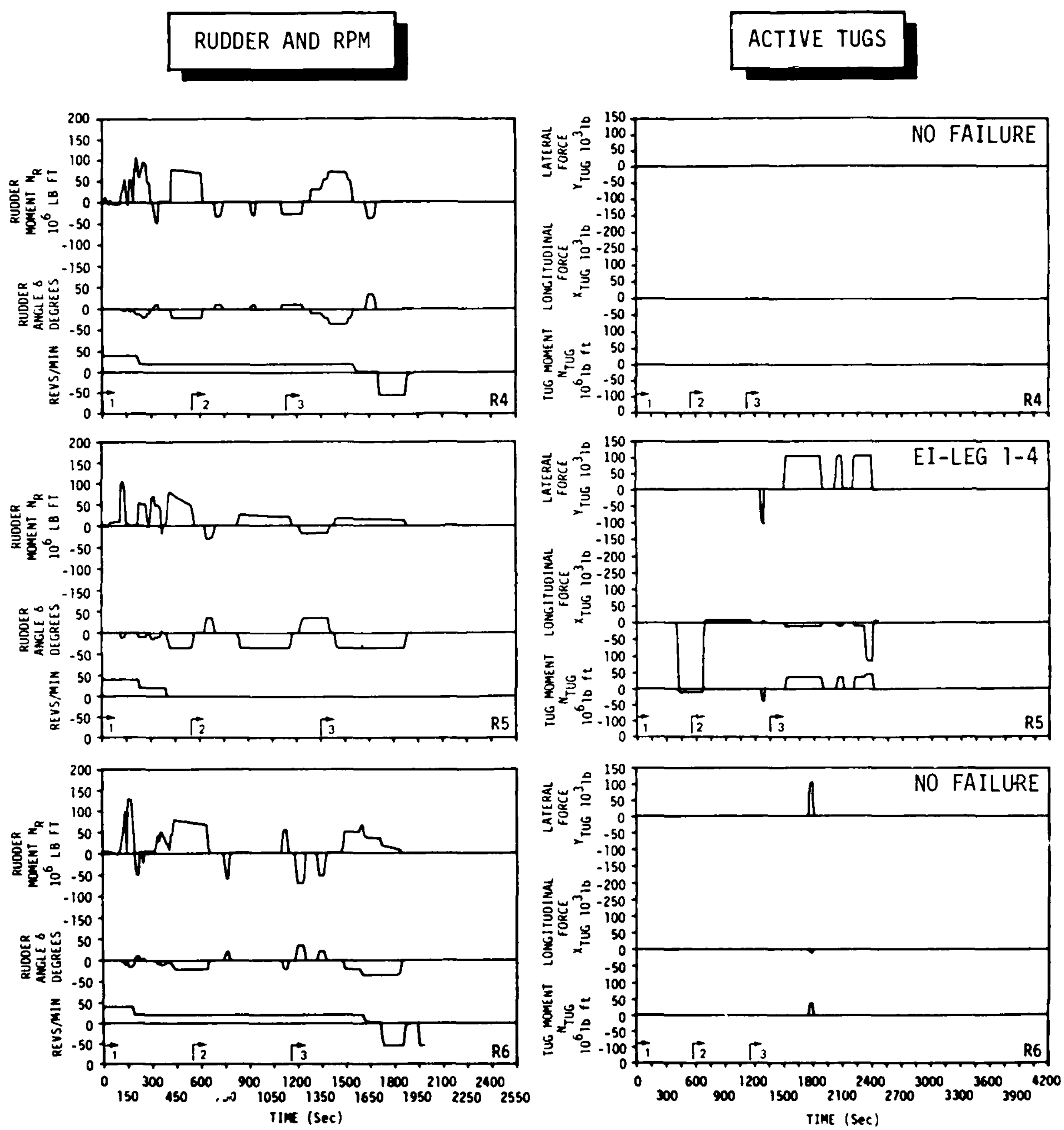


Figure 3-25 (b). Time Variation of Rudder Moment, Rudder Angle and RPM, Tug Forces and Moments, Active Tug Mode, Subject 12 (Cont), Run R4 to R6

SUBJECT 12 CONT

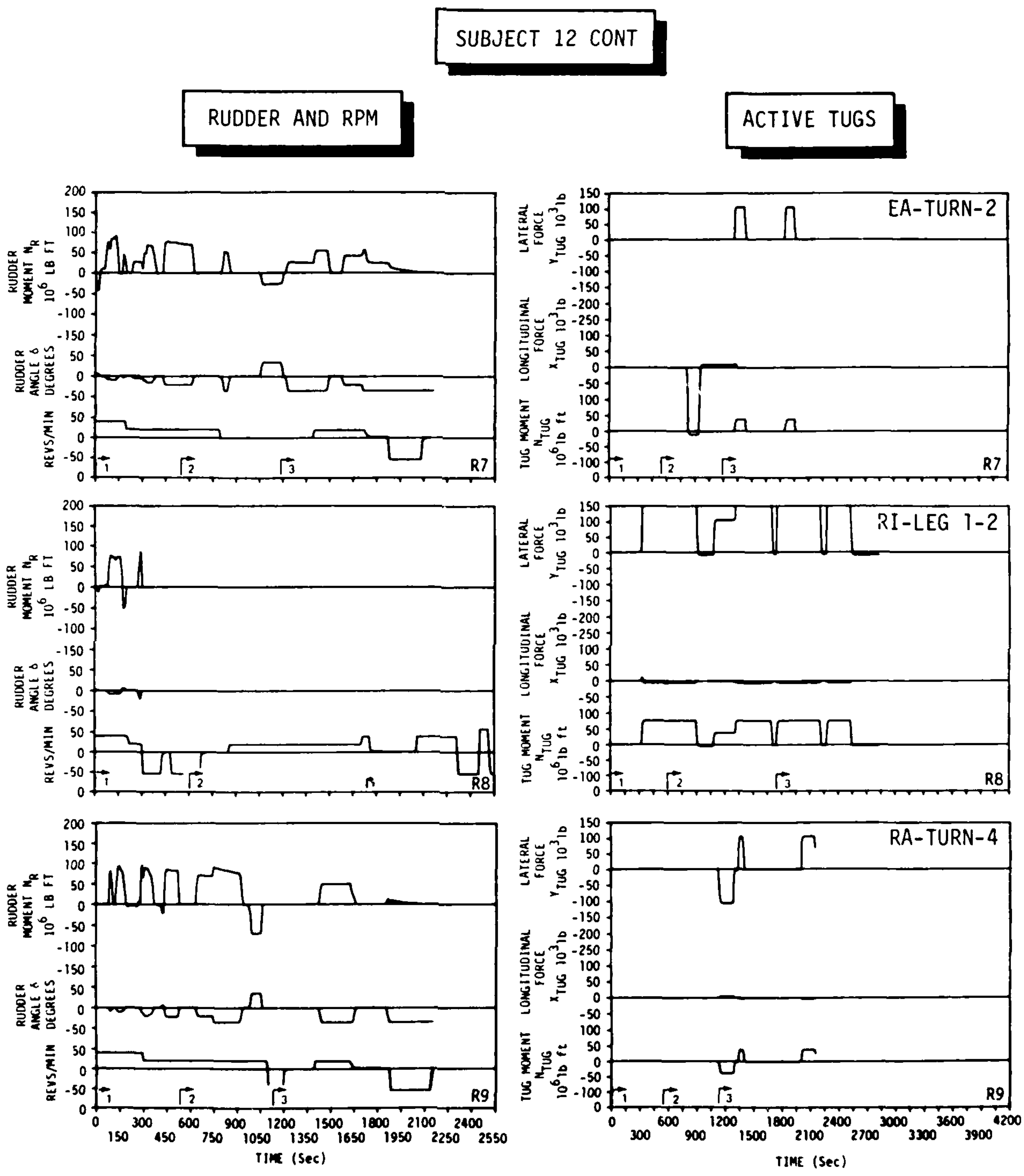


Figure 3-25 (c). Time Variation of Rudder Moment, Rudder Angle and RPM, Tug Forces and Moments, Active Tug Mode, Subject 12 (Cont), Runs R7 to R9

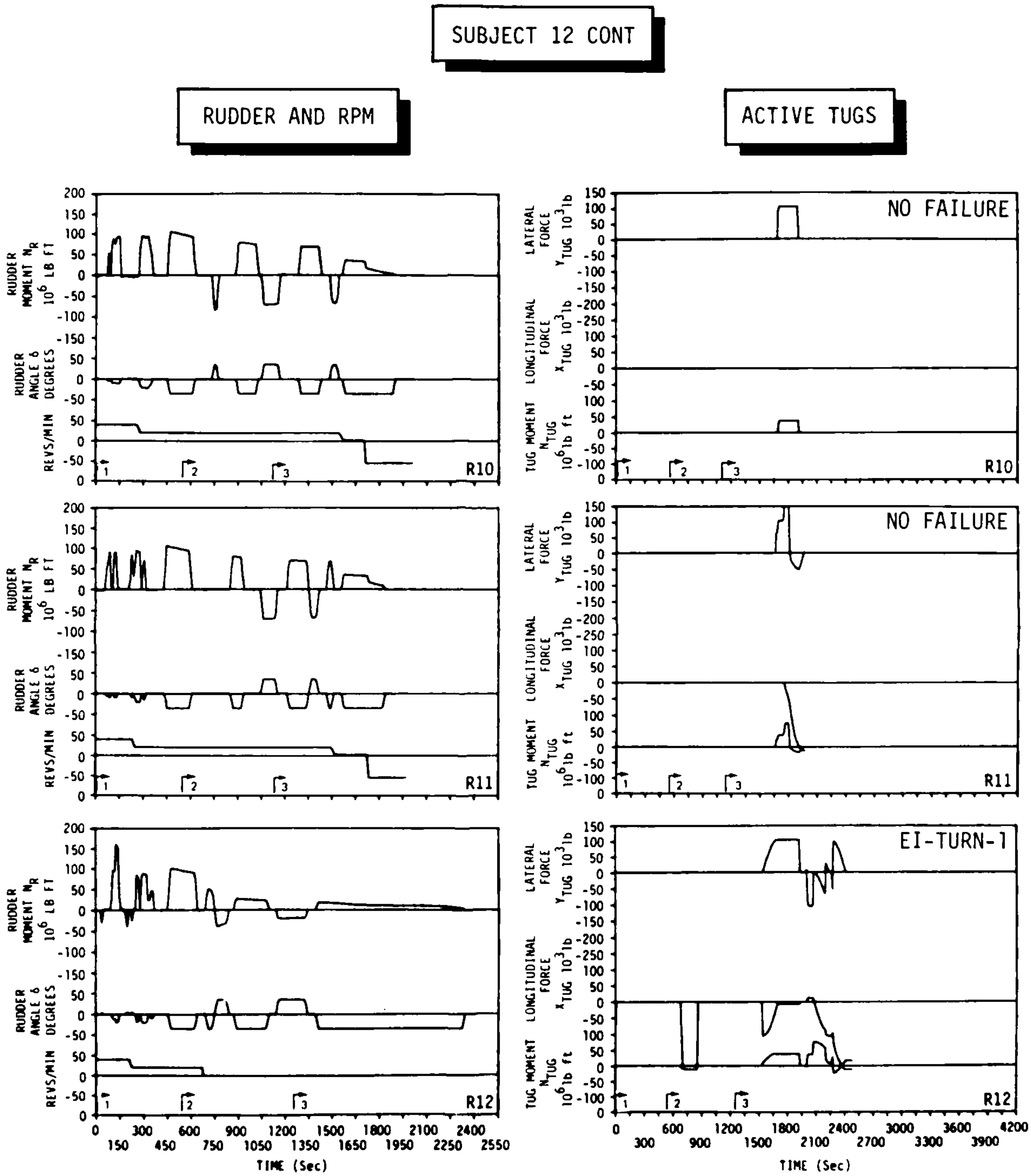


Figure 3-25 (d). Time Variation of Rudder Moment, Rudder Ange and RPM, Tug Forces and Moments, Active Tug Mode, Subject 12 (Cont), Runs R10 to R12

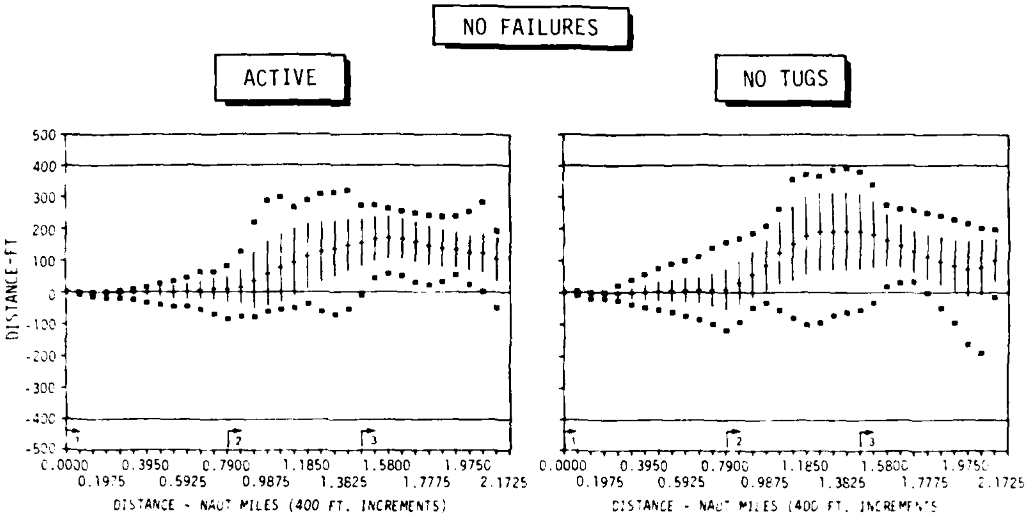


Figure 3-26. Mean Track (dots), Standard Deviation (1/2 vertical line length), and Extremes (■) at 400 Feet Intervals for No Failure Runs with Active Tugs (8000 BHP Total) and No Tugs

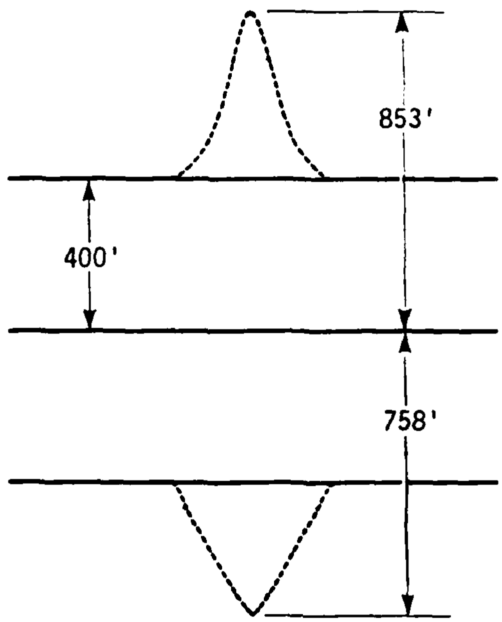


Figure 3-27. Channel Width Variation in the 45° Turn

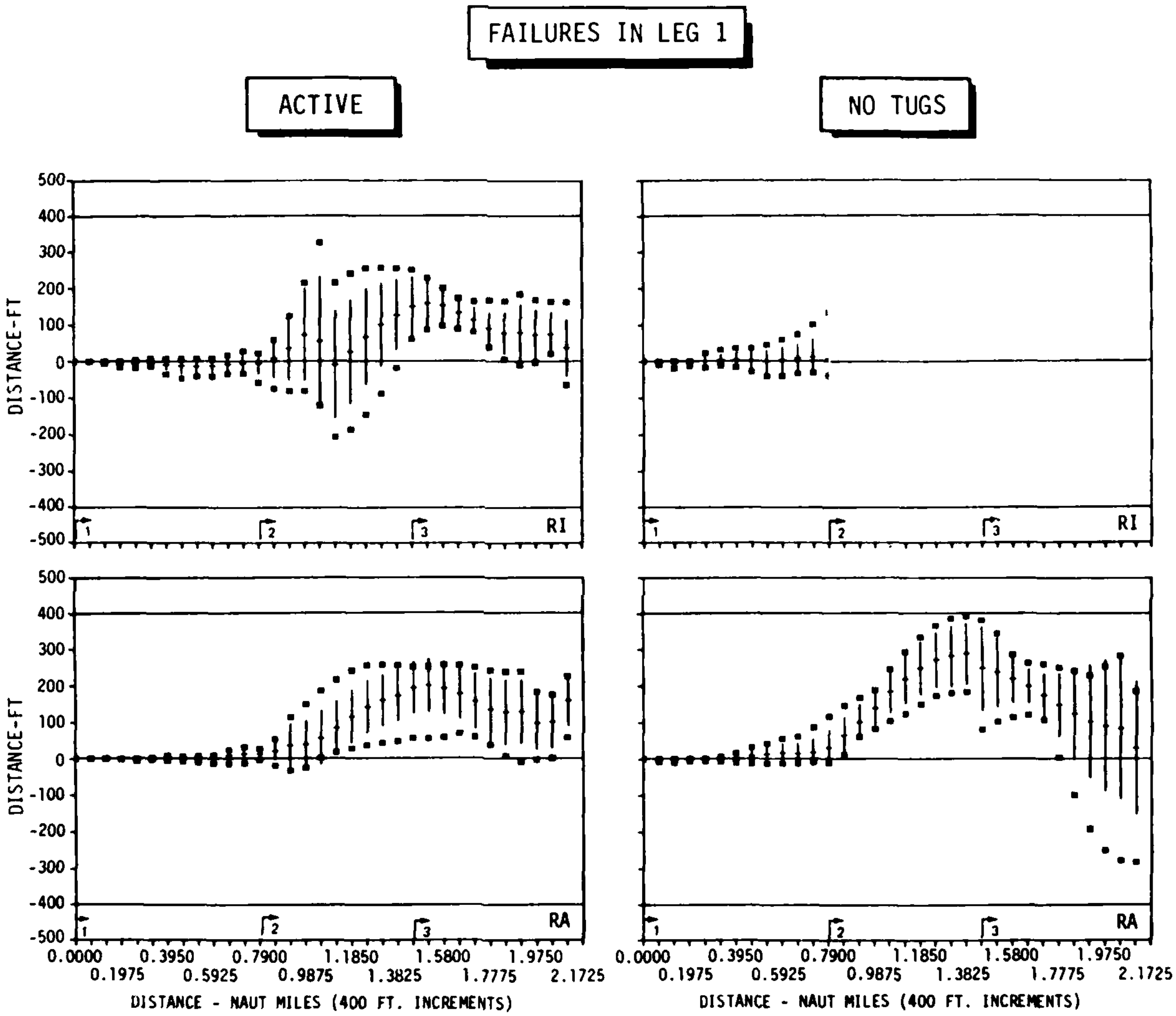


Figure 3-28(a). ***Mean Track (dots), Standard Deviation (1/2 vertical line length), and Extremes (■) at 400 Feet Intervals for Rudder Failures in Leg 1, with Active Tugs and No Tugs***

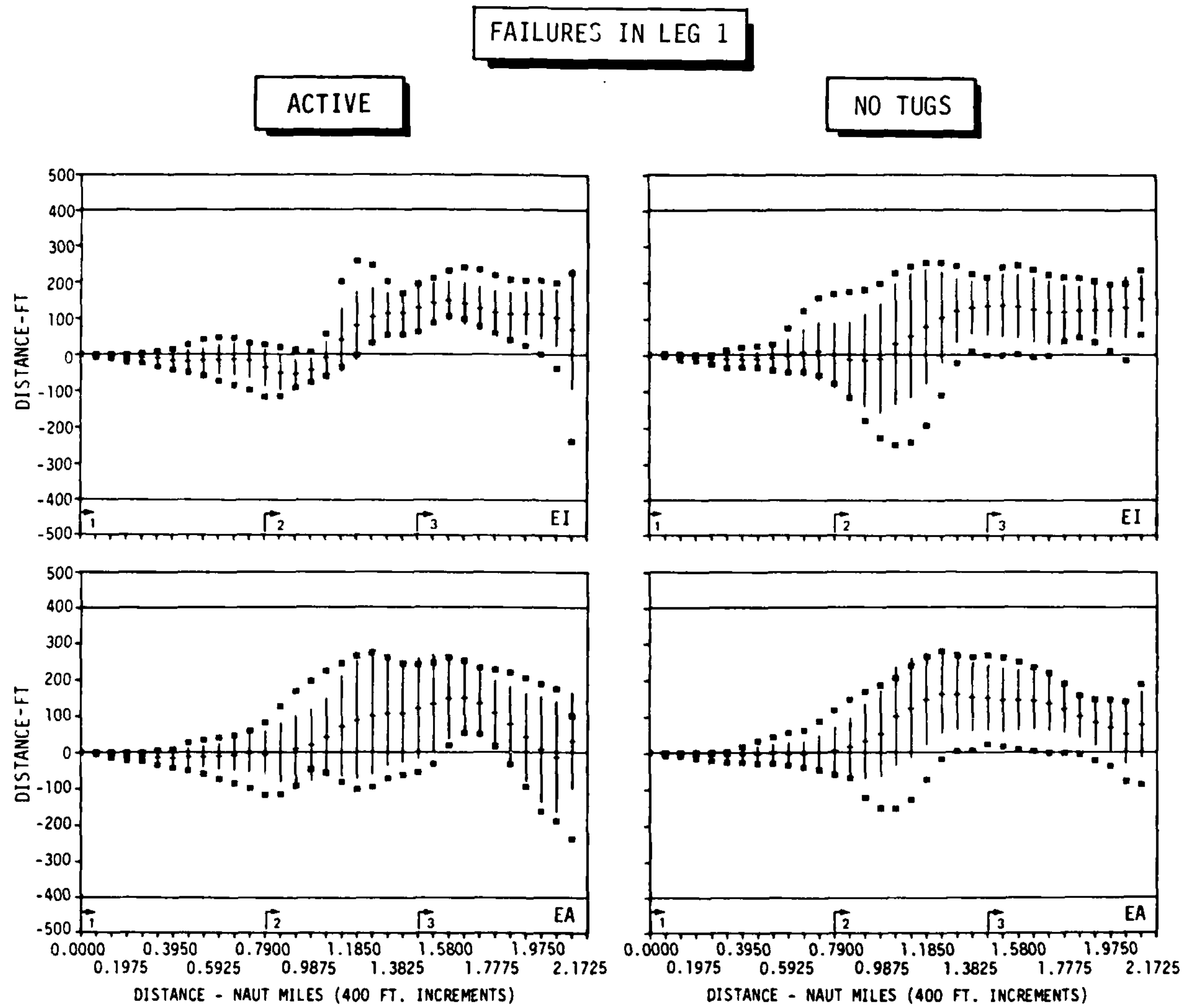


Figure 3-28(b). ***Mean Track (dots), Standard Deviation (1/2 vertical line length), and Extremes (■) at 400 Feet Intervals for Engine Failure in Leg 1, with Active Tugs and No Tugs***

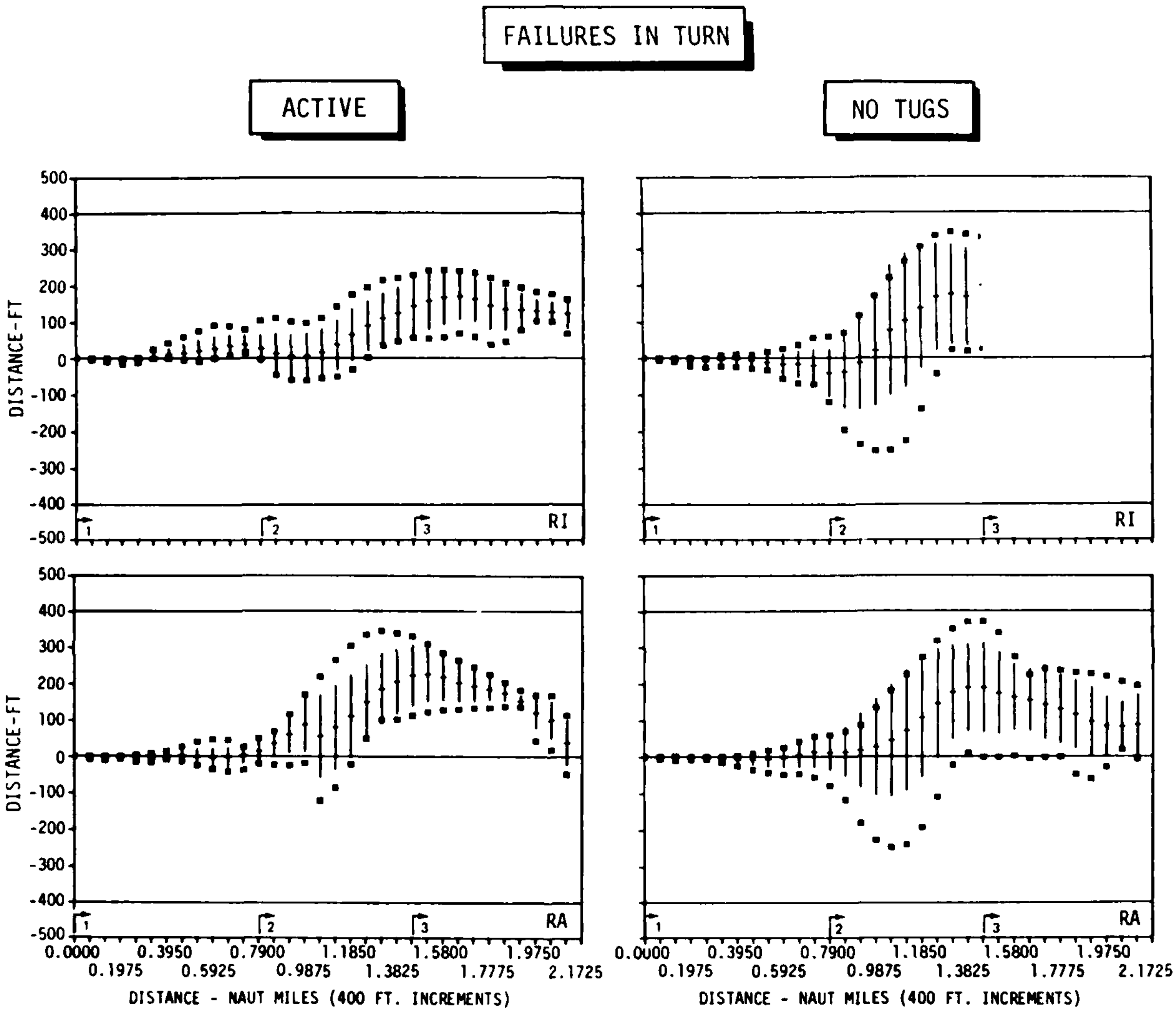


Figure 3-29(a). ***Mean Track (dots), Standard Deviation (1/2 vertical line length), and Extremes (■) at 400 Feet Intervals for Rudder Failures in Turn, with Active Tugs and No Tugs***

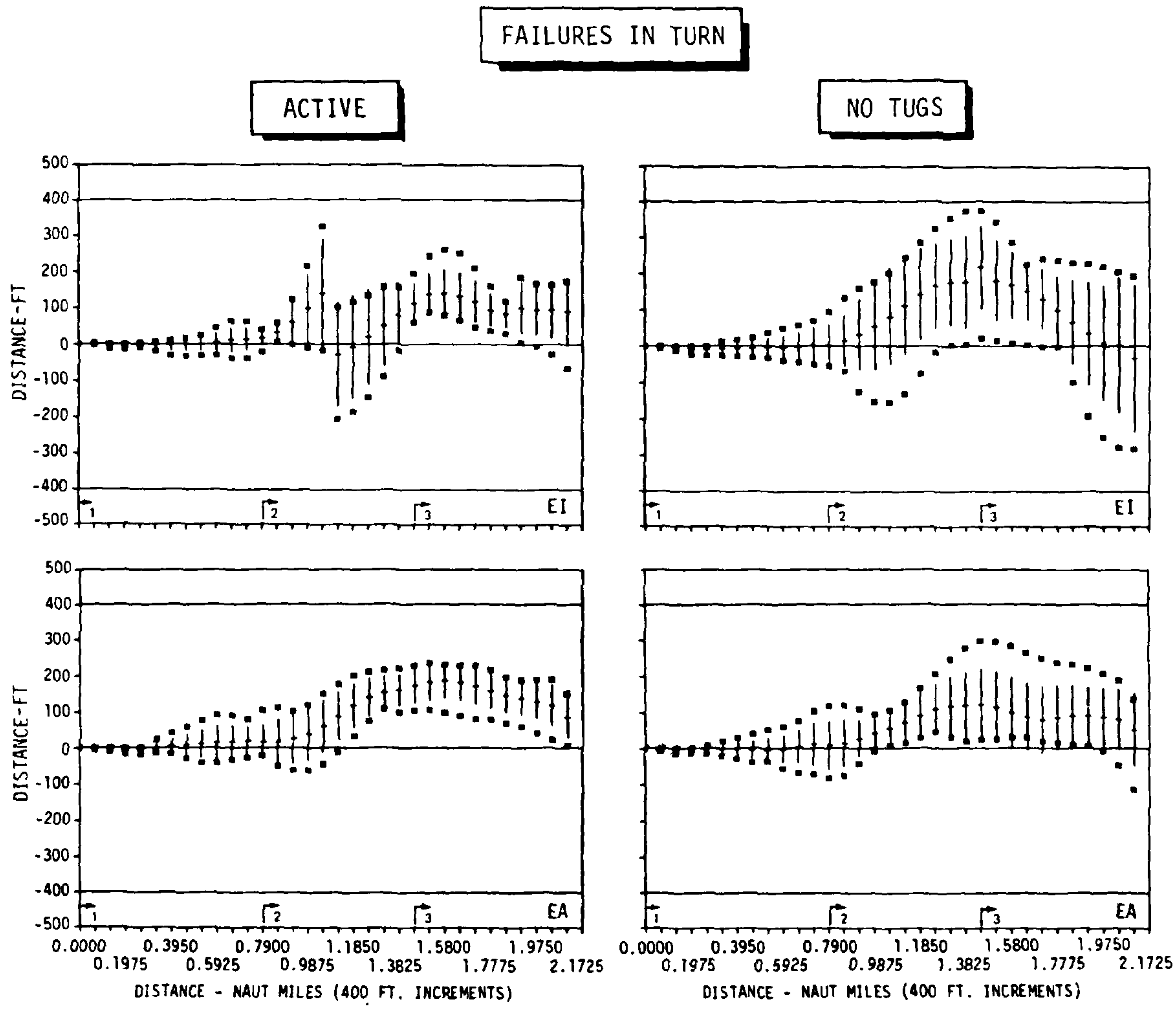


Figure 3-29(b). Mean Track (dots), Standard Deviation (1/2 vertical line length), and Extremes (■) at 400 Feet Intervals for Engine Failures in Turn, with Active Tug and No Tugs

CHAPTER 4

CONCLUSIONS

As a result of the qualitative and quantitative analyses described in this report the following observations and significant conclusions were made:

Non-Failure Cases

- In the absence of mechanical equipment failures pilots generally had little difficulty in completing a successful passage with the 250,000 DWT tanker, a conclusion also reached in the previous investigation. It is only in the final deceleration phase that tug assistance may be desireable, to counteract drift and moment due to the beam wind and following current. Tugs are not generally used in the first leg or in the turn. In the final leg tug use was slight, and occurred with different variations in the degree of use for deceleration, control and yaw moment, or combinations of both. In seven of the twenty-four runs tugs were not used at all.

- The mean track with and without tugs lies to the left of the designated trackline (leg centerlines and transition arc) at all times. In entering leg 3 the mean track is about midway across the left hand side of the channel. This differs from the findings of the previous experiment where the average track lay to the right of channel centerline on entering the turn, crossed over the transition arc about midway in the turn, and entered the third leg about 100 feet to the left of centerline. Hence in this case the mean centerline appears to have been moved bodily about 100 feet to the left. The mean speed of the ship was approximately 0.43 knots higher in the first leg and in the turn than in prior experiments. This higher speed increases the rudder effectiveness and reduces the influence of the wind. There is a decrease in the use of right rudder but an increase in left corrective rudder used, particularly in the final phases. This group of pilots may also have preferred to stay to windward in anticipation of possible mechanical failures occurring.

- With no tugs the standard deviation (consistency) in the turn and the extremes are larger than those when tugs were available, despite the fact that these tugs were not used. It was found, however, that the pilots with tugs used slightly higher mean speeds in leg 1 and the turn, and this perhaps led to the more consistent performance.

- As in the previous experiment, some pilots appeared to use an approximately constant heading technique to cut across the turn parallel to the inner edge, whereas others used an approximately constant turn rate and followed the transition arc quite closely.

- The percentage time that right rudder is used was much higher in all legs in the prior experiment than in this experiment.

The smaller rudder use may be attributed to the higher mean speeds of the ships in this experiment. In addition, a further factor may be the influence of the bank moments on the ship. In this experiment the mean track of the ships lies to the left of track, especially in the third leg and consequently the ship experiences suction forces and clockwise moments from the interaction with the left bank. These moments are counteracted by the application of left rudder. The bank interaction moment opposes the wind moment and consequently reduces the need for corrections using right rudder. Hence the amount of right rudder should be expected to decrease, whereas the amount of left rudder should increase. The largest difference is indeed found to occur in the final leg.

- During the final deceleration phase in leg 3 the engine rpm's are run at full power astern (~-40 rpm). In this case, where the ship speed is still forward ($u > 0$) but engine running astern ($n < 0$), the reverse thrust is close to the maximum that can be exerted by the two 4000 BHP tugs pulling backwards at the stern of the ship (namely 216,000 lb). Consequently the two tugs can compensate adequately for engine power loss in the deceleration mode.

- In the final leg when engines are reversed to provide maximum deceleration and the ship is in forward motion, there is a drastic change in the rudder efficiency and rudder moments. Although the use of full power in reverse leads to a large deceleration force it does not contribute to the rudder effectiveness. For a mean ship speed of 4.5 fps (about 2.7 knots) in this final leg, the rudder moment, using maximum right rudder, equals 8.5×10^6 lb. ft. This is only about one tenth of what could be obtained using the available tug power.

- The swept path in the turn is generally much larger than that in the first leg but decreases in the third leg. When there is no recovery the swept paths in legs 2 and 3 are not significantly different whether tugs are available or not.

Failure Cases

- The highest value of inherent risk occurs in the turn, the next highest in the first leg and the lowest value in the final leg. This is obviously due to the restricted maneuvering area available in this scenario.

- From the rudder and rpm time variations corresponding to non-failure runs it is apparent that the rudder was generally amidship for a relatively large percentage of the time in the turn and in leg 1 and also the rpm's were generally reduced to slow ahead or dead slow. Under these conditions failures occurring in certain locations in either leg but with recovery would not present a problem. Failures without recovery however present a serious problem, more so in the event of a rudder failure than for engine failure.

- With a finite recovery time, the location of the rudder failure can be critical. If it occurs in

leg 1 just at the point when the turn should have been initiated, then control of the ship through the turn is difficult without tug assistance. On the other hand if failure occurred after the turn has been initiated and the ship has developed sufficient turn rate, the loss of rudder for a five-minute period may not be serious. Should the rudder failure occur towards the end of the turn when corrective rudder is required, then again problems may be experienced in transiting the final leg without tug assistance.

o A loss of engine power will not impose such serious consequences. In leg 1 and in the turn where failure occurred the ship has moderate hull speeds (about five knots) at which the rudder can be used very effectively despite the loss of the propeller wash on the rudder following failure. Hence sufficient control can be exercised by the rudder, although the ship will slow down more rapidly due to loss of thrust.

o Calculations of rudder moment at the typical ship and engine speeds at location of failures were made. In the case of a rudder failure and consequently a complete loss of rudder moment, the available tugs could compensate for this loss only if the original rudder angle were less than 20°.

o Similarly in the event of an engine failure it was also shown that due to the reduced propeller wash over the rudder, there was a 30% loss in effective rudder moment. The maximum tug moment available can adequately compensate for this loss if necessary. The loss of engine power becomes more serious as the ship speed decreases, and at very low speeds it is the propeller wash over the rudder that provides the major contribution to the forces and moments.

o The occurrence of a rudder failure at specific locations in the channel and/or without recovery can create a serious situation if tugs are not available to compensate for the loss of turning moment on the ship. The cases of rudder failure without recovery either in the first leg or in the turn caused the pilots to take unique measures to abort their mission when they did not have tug support. In all other cases of failures with or without tugs they continued the transit to the end.

o The following general procedure was adopted by all pilots in the event of a rudder failure without tug assistance. Whether the failure occurs in the first leg or in the turn, the procedure is to immediately brake by putting the engine in full reverse and keeping it there until the failure is corrected or the ship has stopped. The corresponding procedure when tug support is available and failure occurs prior to the turn, is

1) To decelerate immediately by putting the engine in full reverse,

2) At the same time use the tugs to provide the necessary yaw moment to initiate the turn (and further

deceleration if desired), and then essentially to duplicate the rudder control processes that have been lost and,

3) Use the tugs for the final deceleration, where it has been found that tug assistance is advantageous at all times for the 250,000 DWT tanker.

If the turn has already been initiated when the failure occurs there is no attempt to decelerate further by using the engine, which is not touched. Tugs are used to compensate for the loss of rudder by providing correcting yaw moments and lateral forces to balance the wind drift and prevent luffing.

- A loss of engine power does not significantly reduce the rudder efficiency at the ship speeds encountered in the first leg or in the turn. The amount of thrust that is lost is also not a significant quantity and can be very easily compensated for by using tugs if available. If tugs are not available then the ship will slow down more quickly. Consequently the rudder effectiveness will be reduced and larger rudder angles will be required for control.

- The following general procedures were adopted by pilots in the event of an engine failure:

  Effective control is carried out conventionally using the rudder. When tugs are present they are used primarily for deceleration, although they can also supplement the rudder moments. In the final stages they are effectively used for both deceleration and control.

  In this final deceleration phase the ship is totally dependent on the availability of the tugs. This function was carried out primarily by the engine under normal no-failure and rudder failure conditions.

- The contribution of off-track deviation to the combined performance measure is greatest in the turn, next largest in the final leg, and quite low in the first leg in the no-failure condition. There is a significant increase in the third leg for failure conditions when the recovery time is increased.

- The rudder contribution is significantly increased when an engine failure occurs. When the failure takes place in the first leg, significantly more rudder is used to compensate than when failure occurs later. In the turn the difference due to position of failure is not significant. However in the final leg where deceleration is usually performed using the engine, more rudder and tug power are used for deceleration and control; more so when the failure occurs later in the turn.

- In the event of an engine failure in the absence of tug support, values of rudder contribution significantly higher than under the non-failure condition occur in leg 2, and increase with failure time. In leg 3 the difference in rudder contribution between no failure and average failure conditions is insignificant, but

changes significantly when there is no recovery. With tug support, however, the only significant difference with failure time occurs in the third leg. The rudder contribution increases significantly for the average failure time and no further significant increase with extended failure time.

- With rudder failure and no tug support there is a significant effect of failure time in leg 2 on the rudder contribution. Although there is a non-significant change in leg 3 between no failure and average failure, both are significantly different from the case of no recovery. This is due to the fact that the rudder is completely lost in this leg. The same is true when tugs are present.

  The presence of tugs results in the decreased use of rudder in leg 2 for all time-of-failure conditions, and also in the final leg only for the no-recovery condition. For the rudder case, there is significantly more contribution in the turn when tugs are not present and there is no failure, and also in the third leg when recovery takes place.

- The mean longitudinal tug force $\bar{X}_T$ responsible for producing deceleration increases significantly throughout the transit, whether failures take place in the initial leg or in the turn. This retarding force is largest in leg 1 when failure occurs in leg 1, and largest in leg 3 when failure occurs in the turn. In the turn itself the force is essentially independent of the failure location.

- There is a significant increase in $\bar{X}_T$ in the case of an engine failure, especially in the final leg. The value of $\bar{X}_T$ in the third leg increases rapidly as the failure time increases. However, there is no significant difference between the values in the first leg and in the turn.

- In the case of a rudder failure with engine power still available for deceleration, the tugs are used mainly to compensate for the loss of rudder moment rather than deceleration over the major part of the transit.

  As a consequence, the value of the decelerating force does not change significantly in the final (deceleration) leg with the time duration of the failure as it does in the case of an engine failure.

- There is a significantly larger $\bar{Y}_T$ (the lateral tug force that contributes to the turning moment of the ship and to counteracting drift) for the case of rudder failures than for engine failures. This can be related to the fact that when an engine failure occurs tugs are used principally to produce deceleration, and when a rudder failure occurs to produce moments.

  The force is significantly larger as the failure time is increased, but shows no differences due to the actual position of failure. Its value increases with leg, having a maximum value in the terminal leg.

- When failure occurs in the first leg there are significant differences in tug moment contribution between legs 1 and 2 and

between 2 and 3. The highest value (.515) occurs in the turn and the values in the first leg and third leg are not statistically significantly different. This clearly demonstrates the effective use of the tugs for control in the turn (N_{RMS} = 0.72 times maximum possible tug moment), and less in the third leg where they are principally used for deceleration rather than control.

- The *position of failure does not* have any effect on the inherent risk for engine failures with and without tug assistance, or rudder failures without tugs, independent of the length of time the failure lasts. However the position of failure is important when a rudder failure occurs and tugs are present -- the risk is greater when failure occurs in the turn. There is a significant decrease in risk as the failure time is increased, due to the presence of tugs for control.

- The risk is larger for an engine failure than with a rudder failure when the failure occurs in the first leg and tugs are in assistance. There is also a significant increase in risk in the turn when the rudder failure occurs in the turn.

- Higher values of the combined performance measure, J2, are produced by engine failures than by rudder failures. The major contributors to this difference are larger off-track deviation and rudder contributions in the case of engine failures. The inherent risks are essentially identical for the two systems. The highest value always occurs in the turn principally due to distance off-track and rudder contributions.

- There is no difference in J2 in any leg due to failure position for an engine failure and with tug support. For a rudder failure, on the other hand, and with tugs available the value of J2 is larger in the turn when failure occurs in leg 1 than when it occurs in the turn.

REFERENCE

W. McIlroy: Tug Usage For Control and Deceleration in Restricted Waterways. CAORF Technical Report, Simulation Experiment, CAORF 42-8009-02, February 1982 Draft.

APPENDIX A

SAMPLE PILOT INSTRUCTIONS

The following instructions (Figure A-1) were presented, verbally and in printed form, to test subjects in Group 1 (with no tugs) and Group 2 (with two tugs in attendance).

PILOT INSTRUCTIONS

You will be responsible for piloting a 250,000 DWT VLCC, fully loaded into a hypothetical harbor shown in the accompanying chart. The following are the pertinent characteristics of your ship.

Length	1,085 feet
Beam	170 feet
Draft	65 feet
Ahead HP	36,000
Propeller Diameter	29.2 feet
Max. rudder angle	$\pm$ 35^{o}
Rudder area	1,302 ft.^{2}

A channel 800 ft. wide runs from the entrance (midway between buoys 3 and 4) due North until buoy 8 is reached, a distance of 3/4 n mile. The channel changes direction by 45^{o} and the inner portion of the turn is cut off until buoy 8A is reached. Beyond this point the channel centerline is in the northeasterly direction, 45^{o}. On emerging from the turn at station 8A a further 3/4 n mile must be travelled before reaching buoys 11 and 12. The ship speed is 7 knots through the water at the entrance point, and there is a 1 knot flood (following) current directed along the channel centerline and curving appropriately at the bend. A wind of 30 knot average strength and gusting $\pm$ 10 knots around this average value blows from the Northwest (315^{o}) on the average, but fluctuates $\pm$ 30^{o} around this average direction.

The depth of the water in the channel is 75' giving a 10' underkeel clearance, and depth/draft ratio of 1:15. Outside the channel the water depth is 24 feet. You will experience hydrodynamic interactions between your ship and the channel bottom and boundaries in the simulator. However, changes in trim and squat will not be observed.

Figure A-1. Pilot Instructions, Group 1 (No Tugs) and Group 2 (Active Tugs)

You will commence your transit at the midpoint between buoys 3 and 4 as indicated. Your speed through the water will be seven knots, with the 1 knot following current. Your will experience the 30 knot gusting wind from the NW as described above. The following section is added for Group 2 Subjects:

Two tugs, each 4,000 HP, which are highly maneuverable, and more powerful versions of the Wilmington Launch Tug "Tina," will be available at the entrance and will hook up with your ship in the attendance mode. The tugs will be placed in positions to be designated by you. A period of five minutes will pass before these tugs can become effective. Thereafter, a period of two minutes will be required to move a tug from one side of the ship to the other, and a time of one minute will expire before your command can be effected by a tug can contribute maximum thrusts of 108,000 lb. on a continuous basis at any heading and for speeds less than six knots. Full thrust can be generated aft and broadside as well as forward. The basic characteristics of the "Tina" type tug are:

Length 65 ft., beam 26 ft. draft 10.5 ft.,
Displacement tonnage 127.5, BHP 1,000.

The propulsion comprises two diesel engines coupled to 360° steerable propulsion units with propellers in Kort nozzles. The two propellers in Kort nozzles. The two propellers are mounted aft, and the tugboat can operate as a tractor tug when going astern. *The propellers are right-handed*, four bladed type, of 5.33 ft. diameter enclosed in a Kort nozzle.

The accompanying figure shows the position of the attachment points available, and also the convention to be used in giving the tug orders. For example, starboard bow full ahead corresponds to a 108,000 lb. push against the bow attachment point, at 270° to the ship centerline. Starboard bow full reverse corresponds to a 108,000 lb. pull at 90° to the centerline. The tug orders for thrust, in forward and reverse, are full, half, slow, dead slow and stop corresponding to forces of 108,000, 54,000 27,000, 10,800, and zero lb.

The attachment points are located forward and aft of the center of gravity at one third ship length, i.e., ± 360 feet for your ship, at midship in line with the center of gravity, and at the stem and stern (± 542 feet respectively).

Experiment Procedure

Prior to the main experiment, you will be allowed to perform a familiarization run by transiting the channel from beginning to end

Figure A-1. Pilot Instructions, Group 1 (No Tugs) and Group 2 (Active Tugs) (Continued)

in the 250,000 DWT tanker. This will provide you with the opportunity to become familiar with the characteristics of the ship and the scenario. During this run wind, current and tugs will not be present. At all times, during this and subsequent runs, we expect that in your participation at CAORF you will act at all times as you would normally on board a real ship. Therefore, you should treat this simple exercise as though it were a real world transit, and follow a course comparable to one you would normally follow in a similar situation.

You will make twelve transits of the channel under the external environmental forces of wind and current. The following is added for Group 2 Subjects:

and with the 2 tugs in attendance subject to the constraints described previously. You will enter the channel at seven knots and attempt to reduce your speed to zero speed over the ground when you reach the location midway between buoys 11 and 12. This you will accomplish by manipulating the rudder, and the engine rpm, and the tugs in the best manner for a safe transit. During the transit you can expect either a failure of your rudder or your engine (but not both simultaneously) and these may occur at any point.

If the environmental conditions used in the experiment appear to be over severe, it should be understood that the values were selected with the experimental objective in mind.

Engine orders should be given in the telegraph mode (full ahead 60 rpm, half ahead 40 rpm, slow ahead 20 rpm, dead slow 10 rpm). A mate on watch will relay your engine commands and record bell book entries.

The following is added for Group 2 Subjects:

Since you will not have the capability in the simulator to observe the placement of your tugs, we are providing a closed circuit TV monitor in the wheelhouse. The display will indicate the positions and directions of the active tug thrusts (but not their magnitude) by arrows. Where a tug is in attendance, but inactive, it is represented by a square placed in the last active position of the tug. The arrows will be moved and placed in position at the instant your command is answered by the tug.

Figure A-1. Pilot Instructions, Group 1 (No Tugs) and Group 2 (Active Tugs) (Continued)

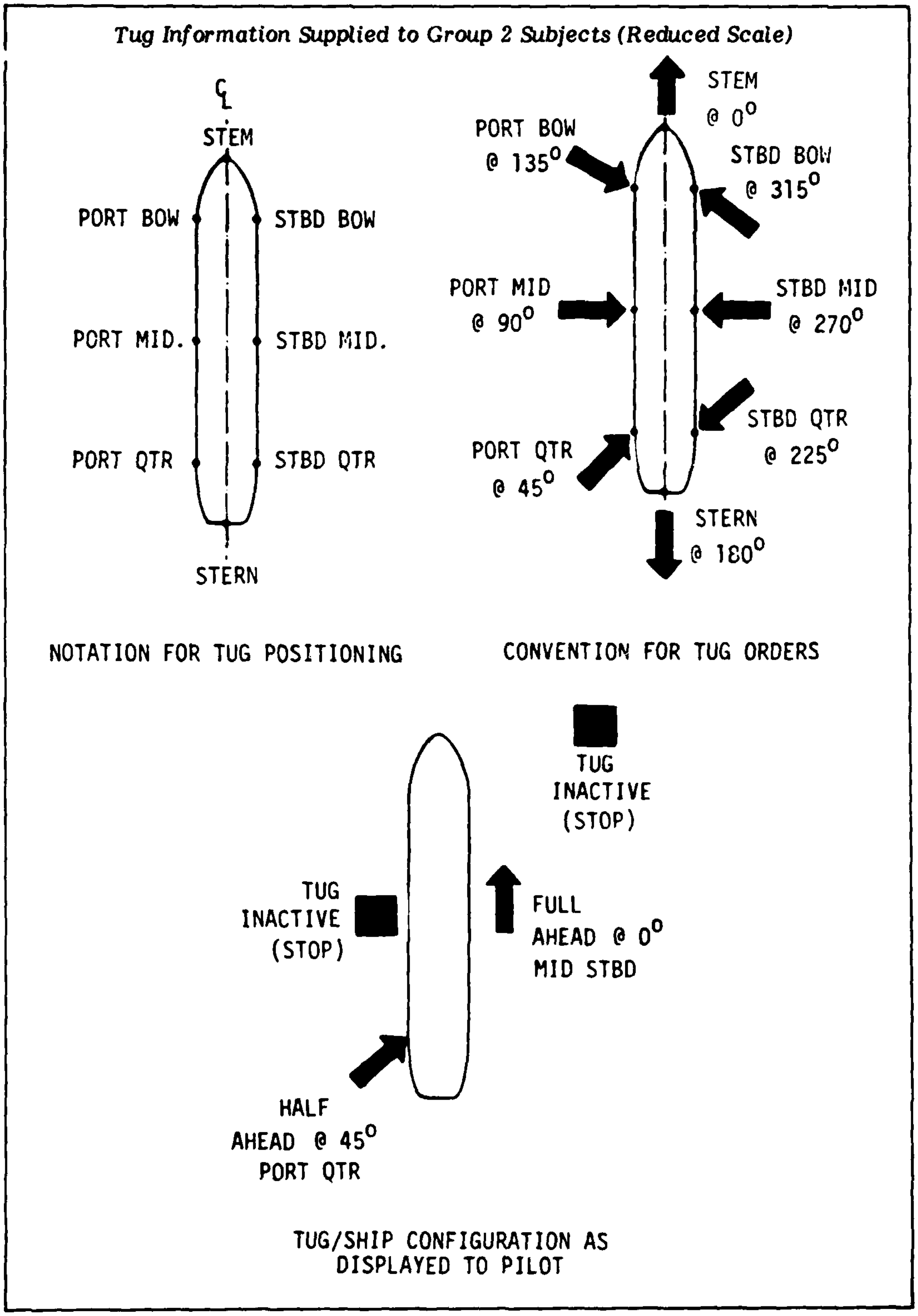


Figure A-1. Pilot Instructions, Group 1 (No Tugs) and Group 2 (Active Tugs) (Continued)

Harbor Information Supplied to All Subjects (Reduced Scale)

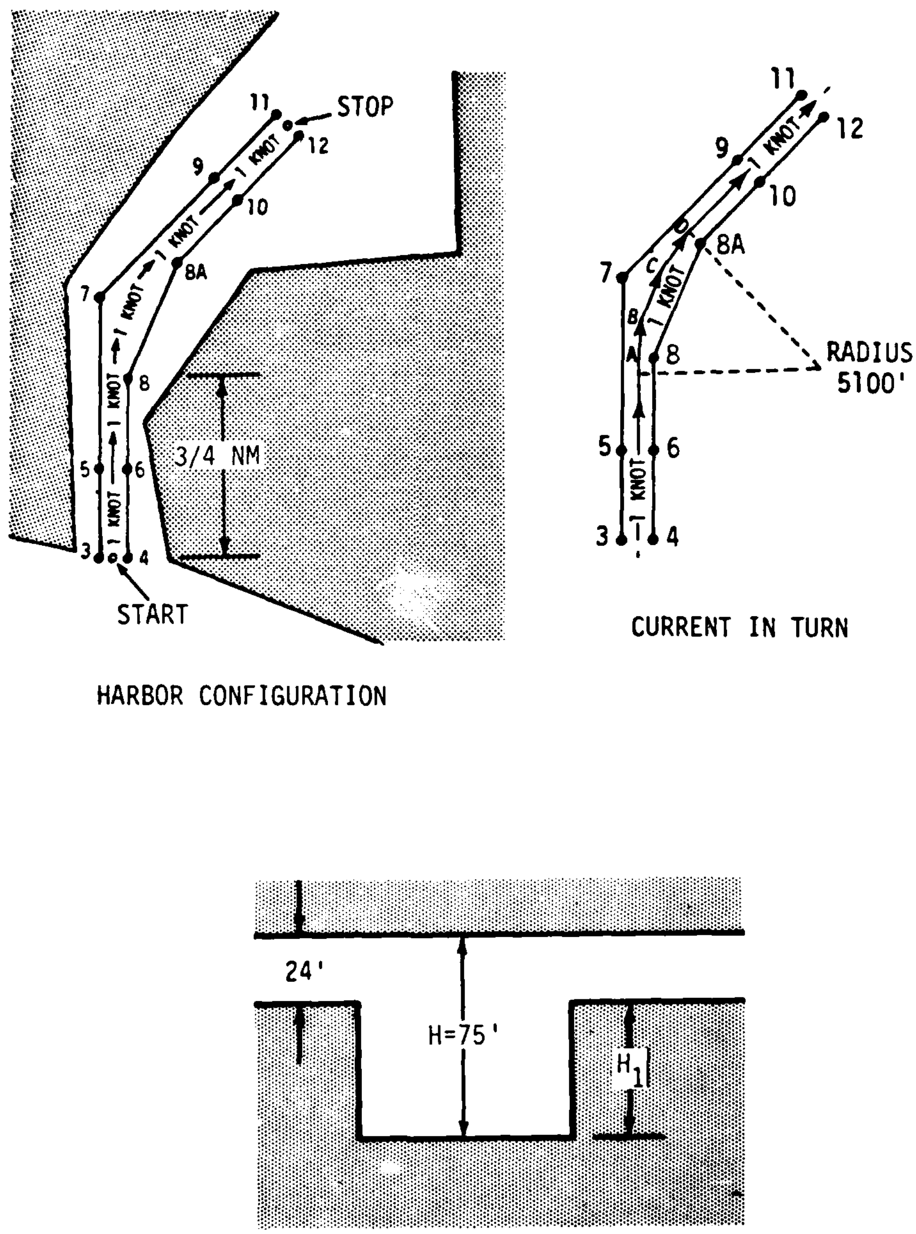


Figure A-1. Pilot Instructions, Group 1 (No Tugs) and Group 2 (Active Tugs) (Continued)

APPENDIX B

STATISTICAL MAIN EFFECTS AND INTERACTIONS

This Appendix presents tables showing the main effects and interactions that were found to be significant for the performance measures treated in the experiment. These tables were utilized in the discussion presented in Chapter 3, Section 3.2.

TABLE B-1. RELATIONSHIP AMONG MEANS FOR TUG MODE (C)

Parameter	No Tugs (C1)	Active Tugs (C2)	Main Effect p Value
Percentage Time Left Rudder	18	15	ns
Percentage Time Right Rudder	38	35	ns
Time Rudder Used in Leg (min.)	6.95	5.91	ns
Swept Path (ft)	245.86	231.79	ns
J1	0.92	1.12	ns
J2	1.41	1.57	ns
J3	1.52	1.76	ns
α_1	0.02	0.06	ns
α_2	0.51	0.52	ns
α_3	0.62	0.71	0.05
Distance Off Track Contribution	0.55	0.70	ns
Rudder Contribution	0.35	0.28	ns
Tug Moment Contribution	0.001^{+}	0.071	0.001
Mean Speed (ft/sec.)	6.50	6.77	ns
Tug $\bar{X}_T$	0.000	0.075	0.001
Tug $\bar{Y}_T$	0.000	0.083	0.001

ns = not significant
$^{+}$ This value should be exactly zero.

TABLE B-2. RELATIONSHIP AMONG MEANS FOR SYSTEM EFFECTED (E)

Parameter	Engine (E1)	Rudder (E2)	Main Effect p Value
Percentage Time Left Rudder	19	14	0.01
Percentage Time Right Rudder	44	29	0.001
Time Rudder Used in Leg (min.)	7.71	5.15	0.001
Swept Path (ft)	234.68	242.97	0.05
J1	1.22	0.81	0.01
J2	1.69	1.28	0.01
J3	1.88	1.42	0.01
α_1	0.06	0.02	0.001
α_2	0.53	0.55	ns
α_3	0.72	0.63	0.05
Distance Off Track Contribution	0.74	0.51	ns
Rudder Contribution	0.40	0.22	0.001
Tug Moment Contribution	0.017	0.055	0.001
Mean Speed (ft/sec.)	6.88	6.38	0.001
Tug $\bar{X}_T$	0.046	0.030	ns
Tug $\bar{Y}_T$	0.030	0.054	0.05

ns = not significant
+ This value should be exactly zero.

TABLE B-3. RELATIONSHIP AMONG MEANS FOR TIME COURSE OF FAILURE (T)

Parameter	Zero (T1)	Average (T2)	Infinite (T3)	Main Effect p Value	Comparison (T) 1-2	1-3	2-3
Percentage Time Left Rudder	21	15	12	0.001	**	**	ns
Percentage Time Right Rudder	37	43	30	0.001	**	**	**
Time Rudder Used in Leg (min.)	6.82	7.50	4.96	0.001	*	**	**
Swept Path (ft)	231.93	234.28	250.26	0.01	ns	**	**
J1	1.11	1.04	0.97	0.05	ns	ns	ns
J2	1.56	1.50	1.34	0.05	ns	ns	ns
J3	1.73	1.71	1.58	0.05	ns	ns	ns
α_1	0.09	0.04	0.04	0.001	*	*	ns
α_2	0.54	0.51	0.41	0.01	ns	ns	**
α_3	0.71	0.72	0.65	0.001	ns	**	**
Distance Off Track Contribution	0.68	0.61	0.58	0.001	ns	*	ns
Rudder Contribution	0.33	0.35	0.28	0.001	ns	*	**
Tug Moment Contribution	0.006	0.037	0.065	0.001	**	**	**
Mean Speed (ft/sec.)	7.12	6.55	6.24	0.001	**	**	ns
Tug $\bar{X}_T$	0.023	0.036	0.054	0.05	ns	*	ns
Tug $\bar{Y}_T$	0.013	0.041	0.071	0.001	**	**	**

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-4. RELATIONSHIP AMONG MEANS FOR POSITION OF FAILURE (P)

Parameter	Leg 1 (P1)	Turn (P2)	Main Effect p Value
Percentage Time Left Rudder	16	16	ns
Percentage Time Right Rudder	36	39	0.05
Time Rudder Used in Leg (min.)	6.27	6.58	ns
Swept Path (ft)	260.61	237.03	ns
J1	0.98	0.99	ns
J2	1.50	1.49	ns
J3	1.73	1.56	ns
α_1	0.10	0.05	ns
α_2	0.50	0.55	ns
α_3	0.73	0.62	ns
Distance Off Track Contribution	0.64	0.61	ns
Rudder Contribution	0.31	0.31	ns
Tug Moment Contribution	0.05	0.02	0.01
Mean Speed (ft/sec.)	6.36	6.87	0.001
Tug $\bar{X}_T$	0.04	0.04	ns
Tug $\bar{Y}_T$	0.05	0.04	ns

ns = not significant
\+ This value should be exactly zero.

TABLE B-5. RELATIONSHIP AMONG MEANS FOR CHANNEL LEG (L)

Parameter	Leg 1	Leg 2	Leg 3	Main Effect p Value	Comparison (L) 1-2	1-3	2-3
Percentage Time Left Rudder	5	21	23	0.001	**	**	ns
Percentage Time Right Rudder	40	37	33	ns	--	--	--
Time Rudder Used in Leg (min.)	4.12	6.10	9.07	0.001	**	**	**
Swept Path (ft)	192.90	268.87	254.70	0.001	**	**	ns
J1	0.26	1.94	0.96	0.001	**	**	ns
J2	0.88	2.59	1.02	0.001	**	ns	**
J3	1.25	2.67	1.14	0.001	**	ns	**
α_1	0.003	0.205	0.02	0.001	**	ns	**
α_2	0.629	0.858	0.08	0.001	**	**	**
α_3	0.999	0.942	0.20	0.001	ns	**	*
Distance Off Track Contribution	0.104	1.335	0.436	0.001	**	**	ns
Rudder Contribution	0.136	0.354	0.449	0.001	**	**	ns
Tug Moment Contribution	0.015	0.043	0.050	0.001	**	**	ns
Mean Speed (ft/sec.)	9.39	6.47	3.95	0.001	**	**	**
Tug $\bar{X}_T$	0.011	0.016	0.086	0.01	ns	**	**
Tug $\bar{Y}_T$	0.010	0.036	0.080	0.001	ns	**	**

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-6. RELATIONSHIP AMONG MEANS FOR SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY LEG (L) FOR PERCENTAGE OF TIME LEFT RUDDER

System Effected (E)		Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
E1	T1	5.8	25.4	27.6	0.001	**	**	ns
	T2	3.8	21.5	19.7		**	**	ns
	T3	5.4	29.7	30.4		**	**	ns
Comparison (T)	1-2	ns	ns	*				
	1-3	ns	ns	ns				
	2-3	ns	ns	**				
E2	T1	4.8	27.4	34.9		**	**	*
	T2	6.0	16.5	24.6		**	**	*
	T3	4.4	3.8	0.0		ns	ns	ns
Comparison (T)	1-2	ns	**	**				
	1-3	ns	**	**				
	2-3	ns	**	**				
Comparison (E)	T1	ns	ns	*				
	T2	ns	ns	ns				
	T3	ns	**	**				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-7. RELATIONSHIP AMONG MEANS FOR SYSTEM EFFECTED (E) BY POSITION OF FAILURE (P) BY LEG (L) FOR PERCENTAGE OF TIME LEFT RUDDER

System Effected (E)		Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
E1	P1	5.3	26.5	22.5	0.05	**	**	ns
	P2	4.7	24.6	29.3		**	**	ns
Comparison (P)	1-2	ns	ns	*				
E2	P1	4.9	16.4	23.3		**	**	ns
	P2	5.2	15.4	16.3		**	**	ns
Comparison (P)	1-2	ns	ns	ns				
Comparison (E)	P1	ns	**	ns				
	P2	ns	**	**				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-8. RELATIONSHIP AMONG MEANS FOR SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY LEG (L) FOR PERCENTAGE OF TIME RIGHT RUDDER

		Leg (L)			Interaction	Comparison (L)		
System Effected (E)		L1	L2	L3	p Value	1-2	1-3	2-3
E1	T1	41.5	38.8	33.5	0.001	ns	ns	ns
	T2	54.2	41.9	52.1		*	ns	*
	T3	43.4	46.3	48.4		ns	ns	ns
Comparison (T)	1-2	*	ns	**				
	1-3	ns	ns	**				
	2-3	*	ns	ns				
E2	T1	40.3	43.0	27.2		ns	**	**
	T2	31.3	38.7	37.0		ns	ns	ns
	T3	31.4	11.0	0.0		**	**	*
Comparison (T)	1-2	ns	ns	*				
	1-3	*	**	**				
	2-3	ns	**	**				
Comparison (E)	T1	ns	ns	**				
	T2	**	ns	ns				
	T3	**	**	**				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-9. RELATIONSHIP AMONG MEANS FOR SYSTEM EFFECTED (E) BY POSITION OF FAILURE (P) BY LEG (L) FOR PERCENTAGE OF TIME RIGHT RUDDER

System Effected (E)		Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
E1	P1	48.6	42.8	43.0	0.01	ns	ns	ns
	P2	44.1	42.0	46.4		ns	ns	ns
Comparison (P)	1-2	ns	ns	ns				
E2	P1	25.3	29.3	18.6		ns	*	**
	P2	43.4	32.5	24.2		**	**	*
Comparison (P)	1-2	**	ns	ns				
Comparison (E)	P1	**	**	**				
	P2	ns	**	**				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-10. RELATIONSHIP AMONG MEANS FOR TIME COURSE OF FAILURE (T) BY POSITION OF FAILURE (P) BY LEG (L) FOR PERCENTAGE OF TIME RIGHT RUDDER

Time Course of Failure (T)		Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
T1	P1	40.3	40.4	24.0	0.001	ns	**	**
	P2	41.4	41.4	36.8		ns	ns	ns
Comparison (P)	1-2	ns	ns	**				
T2	P1	40.2	46.5	44.1		ns	ns	ns
	P2	45.2	34.1	45.0		*	ns	*
Comparison (P)	1-2	ns	**	ns				
T3	P1	30.3	21.2	24.4		ns	ns	ns
	P2	44.6	36.1	24.0		*	**	**
Comparison (P)	1-2	**	**	ns				
Comparison (P1)	1-2	ns	ns	**				
	1-3	*	**	ns				
	2-3	*	**	**				
Comparison (P2)	1-2	ns	ns	*				
	1-3	ns	ns	**				
	2-3	ns	ns	**				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-11. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY SYSTEM EFFECTED (E) BY POSITION OF FAILURE (P) FOR TIME RUDDER USED

Tug Mode (C)		Position of Failure P1	P2	Interaction p Value	Comparison (P)
C1	E1	8.36	8.37	0.05	ns
	E2	5.05	6.00		**
Comparison (E)		**	**		
C2	E1	6.87	7.23		ns
	E2	4.80	4.72		ns
Comparison (E)		**	**		
Comparison (C)	E1	**	**		
	E2	ns	**		

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE B-12. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY TIME COURSE OF FAILURE (T) BY POSITION OF FAILURE (P) FOR TIME RUDDER USED

Tug Mode (C)		Position of Failure P1	P2	Interaction p Value	Comparison (P)
C1	T1	6.94	7.70	0.05	ns
	T2	8.37	8.18		ns
	T3	4.81	5.68		*
Comparison (T)	1-2	**	ns		
	1-3	**	**		
	2-3	**	**		
C2	T1	6.73	5.92		ns
	T2	6.78	6.67		ns
	T3	3.99	5.34		**
Comparison (T)	1-2	ns	ns		
	1-3	**	ns		
	2-3	**	**		
Comparison (C)	T1	ns	**		
	T2	**	**		
	T3	ns	ns		

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE B-13. RELATIONSHIP AMONG MEANS FOR SYSTEM EFFECTED (E) BY POSITION OF FAILURE (P) BY LEG (L) FOR TIME RUDDER USED

System Effected (E)		Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
E1	P1	4.92	7.37	10.56	0.001	**	**	**
	P2	4.43	6.80	12.17		**	**	**
Comparison (P)	1-2	ns	ns	**				
E2	P1	2.77	5.27	6.74		**	**	**
	P2	4.34	4.96	6.79		ns	**	**
Comparison (P)	1-2	**	ns	ns				
Comparison (E)	P1	**	**	**				
	P2	ns	**	**				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-14. RELATIONSHIP AMONG MEANS FOR TIME COURSE OF FAILURE (T) BY POSITION OF FAILURE (P) BY LEG (L) FOR TIME RUDDER USED

Time Course of Failure (T)		Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
T1	P1	4.22	6.79	9.50	0.001	**	**	**
	P2	4.07	6.62	9.73		**	**	**
Comparison (P)	1-2	ns	ns	ns				
T2	P1	4.10	8.15	10.48		**	**	**
	PT2	4.61	5.39	12.29		ns	**	**
Comparison (P)	1-2	ns	**	**				
T3	P1	3.21	4.01	5.98		ns	**	**
	P2	4.48	5.64	6.42		ns	**	ns
Comparison (P)	1-2	*	**	ns				
Comparison (P1)	1-2	ns	*	ns				
	1-3	ns	**	**				
	2-3	ns	**	**				
Comparison (P2)	1-2	ns	ns	**				
	1-3	ns	ns	**				
	2-3	ns	ns	**				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-15. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY LEG (L) FOR TIME RUDDER USED

Time Course of Failure (T)		Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
C1 E1	T1	4.29	7.02	11.42	0.001	**	**	**
	T2	5.58	8.24	12.43		**	**	**
	T3	4.25	8.75	13.34		**	**	**
Comparison (T)	1-2	ns	ns	ns				
	1-3	ns	ns	*				
	2-3	ns	ns	ns				
C1 E2	T1	3.61	7.74	9.84		**	**	**
	T2	3.28	6.78	13.35		**	**	**
	T3	3.28	1.87	0.000		ns	**	*
Comparison (T)	1-2	ns	ns	**				
	1-3	ns	**	**				
	2-3	ns	**	**				
C2 E1	T1	4.19	5.76	7.92		ns	**	**
	T2	5.15	5.52	11.63		ns	**	**
	T3	4.59	7.22	11.46		**	**	**
Comparison (T)	1-2	ns	ns	**				
	1-3	ns	ns	**				
	2-3	ns	*	ns				
C2 E2	T1	4.48	6.31	9.28		ns	**	**
	T2	3.41	6.53	8.12		**	**	*
	T3	3.27	1.46	0.000		*	**	ns
Comparison (T)	1-2	ns	ns	ns				
	1-3	ns	**	**				
	2-3	ns	**	**				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-15. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY LEG (L) FOR TIME RUDDER USED (CONT)

		Comparison (E)		
Tug Mode (C)		L1	L2	L3
C1	T1	ns	ns	*
	T2	**	ns	ns
	T3	ns	**	**
C2	T1	ns	ns	ns
	T2	*	ns	**
	T3	ns	**	**

		Comparison (C)		
System Effected (E)		L1	L2	L3
E1	T1	ns	ns	**
	T2	ns	**	ns
	T3	ns	ns	*
E2	T1	ns	ns	ns
	T2	ns	ns	**
	T3	ns	ns	ns

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE B-16. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY TIME COURSE OF FAILURE (T) BY LEG (L) FOR SWEPT PATH

		Leg (L)			Interaction	Comparison (L)		
Tug Mode		L1	L2	L3	p Value	1-2	1-3	2-3
C1	T1	192.83	272.86	238.68	0.05	**	**	**
	T2	193.83	272.42	246.71		**	**	*
	T3	197.86	282.10	294.64		**	**	ns
Comparison (T)	1-2	ns	ns	ns				
	1-3	ns	ns	**				
	2-3	ns	ns	ns				
C2	T1	190.00	260.93	236.27		**	**	*
	T2	187.46	265.27	240.00		**	**	*
	T3	195.44	259.65	251.10		**	**	ns
Comparison (T)	1-2	ns	ns	ns				
	1-3	ns	ns	ns				
	2-3	ns	ns	ns				
Comparison (C)	T1	ns	ns	ns				
	T2	ns	ns	ns				
	T3	ns	*	*				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-17. RELATIONSHIP AMONG MEANS FOR SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY LEG (L) FOR SWEPT PATH

System Effected (E)		Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
E1	T1	193.68	267.24	236.33	0.05	**	**	**
	T2	191.83	261.54	244.53		**	**	ns
	T3	198.74	264.07	254.13		**	**	ns
Comparison (T)	1-2	ns	ns	ns				
	1-3	ns	ns	ns				
	2-3	ns	ns	ns				
E2	T1	189.15	266.55	238.62		**	**	*
	T2	189.46	276.15	242.17		**	**	**
	T3	194.56	277.69	291.61		**	**	ns
Comparison (T)	1-2	ns	ns	ns				
	1-3	ns	ns	**				
	2-3	ns	ns	**				
Comparison (E)	T1	ns	ns	ns				
	T2	ns	ns	ns				
	T3	ns	ns	*				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-18. RELATIONSHIP AMONG MEANS FOR TIME COURSE OF FAILURE (T) BY LEG (L) FOR J1

Time Course of Failure (T)		Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
T1		0.23	2.03	1.07	0.01	**	**	**
T2		0.28	1.41	1.42		**	**	ns
T3		0.26	2.36	1.57		**	**	*
Comparison (T)	1-2	ns	*	ns				
	1-3	ns	ns	**				
	2-3	ns	**	**				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-19. RELATIONSHIP AMONG MEANS FOR SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY POSITION OF FAILURE (P) FOR J1

System Effected (E)		Position of Failure P1	P2	Interaction p Value	Comparison (P)
E1	T1	1.06	1.22	0.05	ns
	T2	1.31	1.05		ns
	T3	1.31	1.37		ns
Comparison (T)	1-2	ns	ns		
	1-3	ns	ns		
	2-3	ns	ns		
E2	T1	1.22	0.95		ns
	T2	0.88	0.91		ns
	T3	2.04	0.97		**
Comparison (T)	1-2	ns	ns		
	1-3	**	ns		
	2-3	**	ns		
Comparison (E)	T1	ns	ns		
	T2	ns	ns		
	T3	**	ns		

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE B-20. RELATIONSHIP AMONG MEAN FOR SYSTEM EFFECTED (E) BY POSITION OF FAILURE (P) BY LEG (L) FOR J1

	Position of Failure (P)	Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
E1	P1	0.36	2.09	1.22	0.05	**	**	**
	P2	0.25	1.77	1.62		**	**	ns
Comparison (P)	1-2	ns	ns	ns				
E2	P1	0.19	2.41	1.81		**	**	ns
	P2	0.23	1.47	1.21		**	**	ns
Comparison (P)	1-2	ns	**	**				
Comparison (E)	P1	ns	ns	**				
	P2	ns	ns	ns				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-21. RELATIONSHIP AMONG MEANS FOR TIME COURSE OF FAILURE (T) BY LEG (L) FOR J2

Time Course of Failure (T)		Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
T1		0.87	2.68	1.14	0.01	**	ns	**
T2		0.90	2.12	1.49		**	ns	ns
T3		0.88	2.96	1.65		**	**	*
Comparison (T)	1-2	ns	ns	ns				
	1-3	ns	ns	ns				
	2-3	ns	*	ns				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-22. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY SYSTEM EFFECTED (E) BY POSITION OF FAILURE (P) BY LEG (L) FOR J2

Position of Failure (P)		Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
C1 E1	P1	1.05	3.37	1.32	0.05	**	ns	**
	P2	0.91	2.74	1.83		**	**	**
Comparison (P)		ns	**	*				
C1 E2	P1	0.75	2.65	1.020		**	**	*
	P2	0.86	2.48	0.88		**	ns	**
Comparison (P)		ns	ns	ns				
C2 E1	P1	0.93	2.39	1.23		**	ns	**
	P2	0.84	2.12	1.55		**	*	ns
Comparison (P)		ns	ns	ns				
C2 E2	P1	0.89	3.04	1.61		**	**	**
	P2	0.85	1.93	1.45		**	*	*
Comparison (P)		ns	**	ns				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-22. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY SYSTEM EFFECTED (E) BY POSITION OF FAILURE (P) BY LEG (L) FOR J2 (CONT)

		Comparison (E)		
		L1	L2	L3
C1	P1	ns	**	ns
	P2	ns	ns	*
C2	P1	ns	**	ns
	P2	ns	ns	ns

		Comparison (C)		
		L1	L2	L3
E1	P1	ns	**	ns
	P2	ns	*	ns
E2	P1	ns	ns	*
	P2	ns	*	ns

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE B-23. RELATIONSHIP AMONG MEANS FOR TIME COURSE OF FAILURE (T) BY LEG (L) FOR J3

Time Course of Failure (T)		Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
T1		1.23	2.72	1.23	0.001	**	ns	**
T2		1.28	2.23	1.64		**	ns	*
T3		1.25	3.07	1.66		**	**	**
Comparison (T)	1-2	ns	ns	ns				
	1-3	ns	ns	ns				
	2-3	ns	**	ns				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-24. RELATIONSHIP AMONG MEANS FOR SYSTEM EFFECTED (E) BY TIME COURE OF FAILURE (T) BY POSITION OF FAILURE (P) BY LEG (L) FOR α1

No Tug Mode (C1)

	Position of Failure (P)	Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
E1 T1	P1	0.000	0.056	0.013	0.05	ns	ns	ns
	P2	0.000	0.344	0.014		**	ns	**
Comparison (P)	1-2	ns	**	ns				
E1 T2	P1	0.000	0.128	0.017		ns	ns	ns
	P2	0.000	0.037	0.000		ns	ns	ns
Comparison (P)	1-2	ns	ns	ns				
E1 T3	P1	0.016	0.006	0.062		ns	ns	ns
	P2	0.013	0.430	0.063		**	ns	**
Comparison (P)	1-2	ns	**	ns				
E2 T1	P1	0.013	0.447	0.008		**	ns	**
	P2	0.000	0.323	0.005		**	ns	**
Comparison (P)	1-2	ns	ns	ns				
E2 T2	P1	0.000	0.163	0.006		**	ns	**
	P2	0.000	0.097	0.000		ns	ns	ns
Comparison (P)	1-2	ns	ns	ns				
E2 T3	P1	0.000	0.593	0.000		**	**	**
	P2	0.016	0.125	0.000		ns	ns	ns
Comparison (P)	1-2	ns	**	ns				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-24. RELATIONSHIP AMONG MEANS FOR SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY POSITION OF FAILURE (P) BY LEG (L) FOR $\alpha 1$ (CONT)

No Tug Mode (C1)

		Comparison (T)		
		L1	L2	L3
E1 P1	1-2	ns	ns	ns
	1-3	ns	ns	ns
	2-3	ns	ns	ns
E1 P2	1-2	ns	**	ns
	1-3	ns	ns	ns
	2-3	ns	**	ns
E2 P1	1-2	ns	**	ns
	1-3	ns	*	**
	2-3	ns	**	**
E2 P2	1-2	ns	**	ns
	1-3	ns	**	*
	2-3	ns	ns	*

		Comparison (E)		
		L1	L2	L3
P1	T1	ns	**	ns
	T2	ns	ns	ns
	T3	ns	**	**
P2	T1	ns	ns	ns
	T2	ns	ns	ns
	T3	ns	**	ns

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE B-24. RELATIONSHIP AMONG MEANS FOR SYTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY POSITION OF FAILURE (P) BY LEG (L) FOR α1 (CONT)

Active Tug Mode (C2)

	Position of Failure (P)	Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
E1 T1	P1	0.000	0.199	0.000		**	ns	**
	P2	0.000	0.279	0.007		**	ns	**
Comparison (P)	1-2	ns	ns	ns				
E1 T2	P1	0.000	0.008	0.000		ns	ns	ns
	P2	0.000	0.192	0.035		*	ns	*
Comparison (P)	1-2	ns	**	ns				
E1 T3	P1	0.000	0.107	0.006		ns	ns	ns
	P2	0.000	0.179	0.033		*	ns	*
Comparison (P)	1-2	ns	ns	ns				
E2 T1	P1	0.000	0.336	0.013		**	ns	**
	P2	0.000	0.181	0.007		*	ns	*
Comparison (P)	1-2	ns	*	ns				
E2 T2	P1	0.000	0.056	0.000		ns	ns	ns
	P2	0.000	0.305	0.004		**	ns	**
Comparison (P)	1-2	ns	**	ns				
E2 T3	P1	0.013	0.320	0.038		**	ns	**
	P2	0.000	0.019	0.000		ns	ns	ns
Comparison (P)	1-2	ns	**	ns				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-24. RELATIONSHIP AMONG MEANS FOR SYTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY POSITION OF FAILURE (P) BY LEG (L) FOR α1 (CONT)

Active Tug Mode (C2)

		Comparison (T)		
		L1	L2	L3
E1 P1	1-2	ns	*	ns
	1-3	ns	ns	ns
	2-3	ns	ns	ns
E1 P2	1-2	ns	ns	ns
	1-3	ns	ns	ns
	2-3	ns	ns	ns
E2 P1	1-2	ns	**	ns
	1-3	ns	ns	ns
	2-3	ns	**	ns
E2 P2	1-2	ns	ns	ns
	1-3	ns	*	ns
	2-3	ns	**	ns

		Comparison (E)		
		L1	L2	L3
P1	T1	ns	*	ns
	T2	ns	ns	ns
	T3	ns	**	ns
P2	T1	ns	ns	ns
	T2	ns	ns	ns
	T3	ns	*	ns

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE B-24. RELTIONSHIP AMONG MEAN FOR SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY POSITION OF FAILURE (P) BY LEG (L) FOR α1 (CONT)

		Comparison (C)		
		L1	L2	L3
E1 T1	P1	ns	*	ns
	P2	ns	ns	ns
E1 T2	P1	ns	ns	ns
	P2	ns	*	ns
E1 T3	P1	ns	ns	ns
	P2	ns	**	ns
E2 T1	P1	ns	ns	ns
	P2	ns	*	ns
E2 T2	P1	ns	ns	ns
	P2	ns	**	ns
E2 T3	P1	ns	**	**
	P2	ns	ns	*

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE B-25. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY POSITION OF FAILURE (P) FOR α2

		Position of Failure P1	Position of Failure P2	Interaction p Value	Comparison (P)
C1 E1	T1	0.535	0.538	0.01	ns
	T2	0.496	0.502		ns
	T3	0.544	0.574		ns
Comparison (T)	1-2	ns	ns		
	1-3	ns	ns		
	2-3	ns	*		
C1 E2	T1	0.588	0.541		ns
	T2	0.479	0.525		ns
	T3	0.466	0.544		ns
Comparison (T)	1-2	**	ns		
	1-3	**	ns		
	2-3	ns	ns		
C2 E1	T1	0.527	0.549		ns
	T2	0.501	0.535		ns
	T3	0.533	0.528		ns
Comparison (T)	1-2	ns	ns		
	1-3	ns	ns		
	2-3	ns	ns		
C2 E2	T1	0.544	0.534		ns
	T2	0.438	0.598		**
	T3	0.380	0.550		**
Comparison (T)	1-2	**	ns		
	1-3	**	ns		
	2-3	ns	ns		

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE B-25. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY POSITION OF FAILURE (P) FOR α2 (CONT)

		Comparison (E)	
		P1	**P2**
C1	T1	ns	ns
	T2	ns	ns
	T3	ns	ns
C2	T1	ns	ns
	T2	ns	ns
	T3	*	ns

		Comparison (C)	
		P1	**P2**
E1	T1	ns	ns
	T2	ns	ns
	T3	ns	ns
E2	T1	ns	ns
	T2	ns	*
	T3	*	ns

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE B-26. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY LEG (L) FOR $\alpha 2$

	Time Course of Failure (T)	Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
C1 E1	T1	0.629	0.886	0.093	0.001	**	**	**
	T2	0.588	0.842	0.066		**	**	**
	T3	0.629	0.928	0.120		**	**	**
Comparison (T)	1-2	**	ns	ns				
	1-3	ns	ns	ns				
	2-3	**	ns	ns				
C1 E2	T1	0.648	0.938	0.107		**	**	**
	T2	0.645	0.808	0.053		**	**	**
	T3	0.607	0.832	0.075		**	**	**
Comparison (T)	1-2	ns	*	ns				
	1-3	ns	*	ns				
	2-3	ns	ns	ns				
C2 E1	T1	0.651	0.939	0.024		**	**	**
	T2	0.627	0.869	0.059		**	**	**
	T3	0.640	0.847	0.105		**	**	**
Comparison (T)	1-2	ns	ns	ns				
	1-3	ns	ns	ns				
	2-3	ns	ns	ns				
C2 E2	T1	0.631	0.914	0.071		**	**	**
	T2	0.635	0.821	0.098		**	**	**
	T3	0.621	0.674	0.101		ns	**	**
Comparison (T)	1-2	ns	*	ns				
	1-3	ns	**	ns				
	2-3	ns	**	ns				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-26. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY LEG (L) FOR α2 (CONT)

		Comparison (E)		
		L1	L2	L3
C1	T1	ns	ns	ns
	T2	ns	ns	ns
	T3	ns	*	ns
C2	T1	ns	ns	ns
	T2	ns	ns	ns
	T3	ns	**	ns

		Comparison (C)		
		L1	L2	L3
E1	T1	ns	ns	ns
	T2	ns	ns	ns
	T3	ns	ns	ns
E2	T1	ns	ns	ns
	T2	ns	ns	ns
	T3	ns	**	ns

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE B-27. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY SYSTEM EFFECTED (E) BY POSITION OF FAILURE (P) BY LEG (L) FOR α2

	Position of Failure (P)	Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
C1 E1	P1	0.617	0.872	0.085	0.01	**	**	**
	P2	0.614	0.899	0.101		**	**	**
Comparison (P)		ns	ns	ns				
C1 E2	P1	0.634	0.826	0.073		**	**	**
	P2	0.633	0.893	0.084		**	**	**
Comparison (P)		ns	*	ns				
C2 E1	P1	0.645	0.871	0.045		**	**	**
	P2	0.634	0.899	0.080		**	**	**
Comparison (P)		ns	ns	ns				
C2 E2	P1	0.628	0.676	0.058		ns	**	**
	P2	0.630	0.930	0.122		**	**	**
Comparison (P)		ns	**	*				

** $p < 0.01$ * $p < 0.05$ ns = not significant

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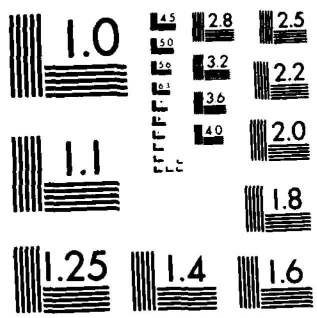

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TABLE B-27. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY SYSTEM EFFECTED (E) BY POSITION OF FAILURE (P) BY LEG (L) FOR α2 (CONT)

		Comparison (E)		
		L1	L2	L3
C1	P1	ns	ns	ns
	P2	ns	ns	ns
C2	P1	ns	**	ns
	P2	ns	ns	ns

		Comparison (C)		
		L1	L2	L3
E1	P1	ns	ns	ns
	P2	ns	ns	ns
E2	P1	ns	**	ns
	P2	ns	ns	ns

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE B-28. RELATIONSHIP AMONG MEANS FOR SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY POSITION OF FAILURE (P) BY LEG (L) FOR α2

	Position of Failure (P)	Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
E1 T1	P1	0.640	0.907	0.039	0.001	**	**	**
	P2	0.635	0.918	0.078		**	**	**
Comparison (P)	1-2	ns	ns	ns				
E1 T2	P1	0.599	0.820	0.076		**	**	**
	P2	0.616	0.891	0.049		**	**	**
Comparison (P)	1-2	ns	ns	ns				
E1 T3	P1	0.648	0.887	0.080		**	**	**
	P2	0.621	0.887	0.145		**	**	**
Comparison (P)	1-2	ns	ns	ns				
E2 T1	P1	0.643	0.947	0.107		**	**	**
	P2	0.636	0.905	0.070		**	**	**
Comparison (P)	1-2	ns	ns	ns				
E2 T2	P1	0.634	0.704	0.037		ns	**	**
	P2	0.646	0.925	0.115		**	**	**
Comparison (P)	1-2	ns	**	ns				
E2 T3	P1	0.615	0.602	0.052		ns	ns	**
	P2	0.613	0.905	0.124		**	**	**
Comparison (P)	1-2	ns	**	ns				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-28. RELATIONSHIP AMONG MEANS FOR SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY POSITION OF FAILURE (P) BY LEG (L) FOR α2 (CONT)

		Comparison (T)		
		L1	L2	L3
E1 P1	1-2	ns	ns	ns
	1-3	ns	ns	ns
	2-3	ns	ns	ns
E1 P2	1-2	ns	ns	ns
	1-3	ns	ns	ns
	2-3	ns	ns	ns
E2 P1	1-2	ns	**	ns
	1-3	ns	**	ns
	2-3	ns	ns	ns
E2 P2	1-2	ns	ns	ns
	1-3	ns	ns	ns
	2-3	ns	ns	ns

		Comparison (E)		
		L1	L2	L3
P1	T1	ns	ns	ns
	T2	ns	**	ns
	T3	ns	**	ns
P2	T1	ns	ns	ns
	T2	ns	ns	ns
	T3	ns	ns	ns

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE B-29. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY LEG (L) FOR α3

	Time Course of Failure (T)	Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
C1 E1	T1	1.000	0.934	0.188	0.001	ns	**	**
	T2	1.000	0.923	0.262		ns	**	**
	T3	1.000	0.980	0.277		ns	**	**
Comparison (T)	1-2	ns	ns	ns				
	1-3	ns	ns	ns				
	2-3	ns	ns	ns				
C1 E2	T1	1.000	0.964	0.191		ns	**	**
	T2	1.000	0.915	0.280		ns	**	**
	T3	0.990	0.943	0.140		ns	**	**
Comparison (T)	1-2	ns	ns	ns				
	1-3	ns	ns	ns				
	2-3	ns	ns	ns				
C2 E1	T1	1.000	0.978	0.110		ns	**	**
	T2	1.000	0.970	0.134		ns	**	**
	T3	1.000	0.963	0.235		ns	**	**
	1-2	ns	ns	ns				
	1-3	ns	ns	*				
	2-3	ns	ns	*				
C2 E2	T1	1.000	0.961	0.169		ns	**	**
	T2	1.000	0.948	0.202		ns	**	**
	T3	1.000	0.825	0.247		**	**	**
Comparison (T)	1-2	ns	ns	ns				
	1-3	ns	*	ns				
	2-3	ns	ns	ns				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-29. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY LEG (L) FOR α3 (CONT)

		Comparison (E)		
		L1	L2	L3
C1	T1	ns	ns	ns
	T2	ns	ns	ns
	T3	ns	ns	**
C2	T1	ns	ns	ns
	T2	ns	ns	ns
	T3	ns	*	ns

		Comparison (C)		
		L1	L2	L3
E1	T1	ns	ns	ns
	T2	ns	ns	*
	T3	ns	ns	ns
E2	T1	ns	ns	ns
	T2	ns	ns	ns
	T3	ns	*	**

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE B-30. RELATIONSHIP AMONG MEANS FOR SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY POSITION OF FAILURE (P) BY LEG (L) FOR α3

	Position of Failure (P)	Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
E1 T1	P1	1.000	0.947	0.115	0.001	ns	**	**
	P2	1.000	0.966	0.183		ns	**	**
Comparison (P)	1-2	ns	ns	ns				
E1 T2	P1	1.000	0.945	0.228		ns	**	**
	P2	1.000	0.948	0.168		ns	**	**
Comparison (P)	1-2	ns	ns	ns				
E1 T3	P1	1.000	0.983	0.196		ns	**	**
	P2	1.000	0.960	0.316		ns	**	**
Comparison (P)	1-2	ns	ns	**				
E2 T1	P1	1.000	0.986	0.219		ns	**	**
	P2	1.000	0.939	0.141		ns	**	**
Comparison (P)	1-2	ns	ns	*				
E2 T2	P1	1.000	0.899	0.199		ns	**	**
	P2	1.000	0.964	0.283		ns	**	**
Comparison (P)	1-2	ns	ns	*				
E2 T3	P1	0.990	0.798	0.161		**	**	**
	P2	1.000	0.970	0.144		ns	**	**
Comparison (P)	1-2	ns	**	ns				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-30. RELATIONSHIP AMONG MEANS FOR SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY POSITION OF FAILURE (P) BY LEG (L) FOR α3 (CONT)

		Comparison (T)		
		L1	L2	L3
E1 P1	1-2	ns	ns	*
	1-3	ns	ns	ns
	2-3	ns	ns	ns
E1 P2	1-2	ns	ns	ns
	1-3	ns	ns	**
	2-3	ns	ns	**
E2 P1	1-2	ns	*	ns
	1-3	ns	**	**
	2-3	ns	*	**
E2 P2	1-2	ns	ns	**
	1-3	ns	ns	**
	2-3	ns	ns	**

		Comparison (E)		
		L1	L2	L3
P1	T1	ns	ns	*
	T2	ns	ns	ns
	T3	ns	**	**
P2	T1	ns	ns	ns
	T2	ns	ns	**
	T3	ns	ns	**

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE B-31. RELATIONSHIP AMONG MEANS FOR TIME COURSE OF FAILURE (T) BY LEG (L) FOR DISTANCE OFF-TRACK CONTRIBUTION

Time Course of Failure (T)		Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
T1		0.11	1.36	0.58	0.01	**	ns	**
T2		0.11	0.86	0.85		**	**	ns
T3		0.10	1.78	1.02		**	**	*
Comparison (T)	1-2	ns	ns	ns				
	1-3	ns	ns	**				
	2-3	ns	**	*				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-32. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY TIME COURSE OF FAILURE (T) BY POSITION OF FAILURE (P) FOR RUDDER CONTRIBUTION

Tug Mode (C)		Position of Failure P1	Position of Failure P2	Interaction p Value	Comparison (P)
C1	T1	0.354	0.387	0.05	ns
	T2	0.399	0.368		ns
	T3	0.281	0.296		ns
Comparison (T)	1-2	ns	ns		
	1-3	*	**		
	2-3	**	*		
C2	T1	0.319	0.259		ns
	T2	0.323	0.314		ns
	T3	0.189	0.263		*
Comparison (T)	1-2	ns	ns		
	1-3	**	ns		
	2-3	**	ns		
Comparison (C)	T1	ns	**		
	T2	*	ns		
	T3	**	ns		

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE B-33. RELATIONSHIP AMONG MEANS FOR SYSTEM EFFECTED (E) BY POSITION OF FAILURE (P) BY LEG (L) FOR RUDDER CONTRIBUTION

System Effected (E)		Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
E1	P1	0.209	0.467	0.540	0.001	**	**	ns
	P2	0.140	0.419	0.638		**	**	**
Comparison (P)	1-2	*	ns	**				
E2	P1	0.060	0.277	0.311		**	**	ns
	P2	0.134	0.251	0.306		**	**	ns
Comparison (P)	1-2	*	ns	ns				
Comparison (E)	P1	**	**	**				
	P2	ns	**	**				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-34. RELATIONSHIP AMONG MEANS FOR TIME COURSE OF FAILURE (T) BY POSITION OF FAILURE (P) BY LEG (L) FOR RUDDER CONTRIBUTION

	Position of Failure (P)	Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
T1	P1	0.129	0.414	0.466	0.05	**	**	ns
	P2	0.121	0.377	0.471		**	**	*
Comparison (P)	1-2	ns	ns	ns				
T2	P1	0.154	0.447	0.481		**	**	ns
	P2	0.149	0.305	0.569		**	**	**
Comparison (P)	1-2	ns	**	*				
T3	P1	0.120	0.256	0.330		**	**	ns
	P2	0.141	0.322	0.376		**	**	ns
Comparison (P)	1-2	ns	ns	ns				
Comparison (P1)	1-2	ns	ns	ns				
	1-3	ns	**	**				
	2-3	ns	**	**				
Comparison (P2)	1-2	ns	ns	*				
	1-3	ns	ns	*				
	2-3	ns	ns	**				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-35. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY LEG (L) FOR RUDDER CONTRIBUTION

	Time Course of Failure (T)	Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
C1 E1	T1	0.131	0.420	0.544	0.05	**	**	*
	T2	0.243	0.558	0.598		**	**	ns
	T3	0.186	0.592	0.782		**	**	**
Comparison (T)	1-2	*	*	ns				
	1-3	ns	**	**				
	2-3	ns	ns	**				
C1 E2	T1	0.112	0.506	0.509		**	**	ns
	T2	0.084	0.287	0.530		**	**	**
	T3	0.084	0.090	0.000		ns	ns	ns
Comparison (T)	1-2	ns	**	ns				
	1-3	ns	**	**				
	2-3	ns	**	**				
C2 E1	T1	0.128	0.311	0.406		**	**	ns
	T2	0.183	0.357	0.573		**	**	**
	T3	0.175	0.419	0.630		**	**	**
Comparison (T)	1-2	ns	ns	**				
	1-3	ns	ns	**				
	2-3	ns	ns	ns				
C2 E2	T1	0.129	0.345	0.416		**	**	ns
	T2	0.096	0.302	0.399		**	**	ns
	T3	0.077	0.055	0.000		ns	ns	ns
Comparison (T)	1-2	ns	ns	ns				
	1-3	ns	**	**				
	2-3	ns	**	**				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-35. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY LEG (L) FOR RUDDER CONTRIBUTION (CONT)

		Comparison (E)		
		L1	L2	L3
C1	T1	ns	ns	ns
	T2	**	**	ns
	T3	*	**	**
C2	T1	ns	ns	ns
	T2	ns	ns	**
	T3	ns	**	**

		Comparison (C)		
		L1	L2	L3
E1	T1	ns	*	*
	T2	ns	**	ns
	T3	ns	**	**
E2	T1	ns	**	ns
	T2	ns	ns	*
	T3	ns	ns	ns

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE B-36. RELATIONSHIP AMONG MEANS FOR SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY POSITION OF FAILURE (P) BY LEG (L) FOR TUG CONTRIBUTION+

No Tug Mode, (C1)

	Position of Failure (P)	Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
E1 T1	P1	0.000	0.000	0.003	0.05	ns	ns	ns
	P2	0.000	0.000	0.002		ns	ns	ns
Comparison (P)	1-2	ns	ns	ns				
E1 T2	P1	0.000	0.000	0.003		ns	ns	ns
	P2	0.000	0.000	0.002		ns	ns	ns
Comparison (P)	1-2	ns	ns	ns				
E1 T3	P1	0.000	0.000	0.000		ns	ns	ns
	P2	0.000	0.000	0.000		ns	ns	ns
Comparison (P)	1-2	ns	ns	ns				
E2 T1	P1	0.000	0.000	0.002		ns	ns	ns
	P2	0.000	0.000	0.003		ns	ns	ns
Comparison (P)	1-2	ns	ns	ns				
E2 T2	P1	0.002	0.001	0.002		ns	ns	ns
	P2	0.000	0.002	0.002		ns	ns	ns
Comparison (P)	1-2	ns	ns	ns				
E2 T3	P1	0.003	0.000	0.000		ns	ns	ns
	P2	0.000	0.002	0.005		ns	ns	ns
Comparison (P)	1-2	ns	ns	ns				

** $p < 0.01$ * $p < 0.05$ ns = not significant

+ All the values in this table should be exactly zero since in no tug mode.

TABLE B-36. RELATIONSHIP AMONG MEANS FOR SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY POSITION OF FAILURE (P) BY LEG (L) FOR TUG CONTRIBUTION+ (CONT)

		Comparison (T)		
		L1	L2	L3
E1 P1	1-2	ns	ns	ns
	1-3	ns	ns	ns
	2-3	ns	ns	ns
E1 P2	1-2	ns	ns	ns
	1-3	ns	ns	ns
	2-3	ns	ns	ns
E2 P1	1-2	ns	ns	ns
	1-3	ns	ns	ns
	2-3	ns	ns	ns
E2 P2	1-2	ns	ns	ns
	1-3	ns	ns	ns
	2-3	ns	ns	ns

		Comparison (E)		
		L1	L2	L3
P1	T1	ns	ns	ns
	T2	ns	ns	ns
	T3	ns	ns	ns
P2	T1	ns	ns	ns
	T2	ns	ns	ns
	T3	ns	ns	ns

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE B-37. RELATIONSHIP AMONG MEANS FOR SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY POSITION OF FAILURE (P) BY LEG (L) FOR TUG CONTRIBUTION

Active Tug Mode (C2)

	Position of Failure (P)	Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
E1 T1	P1	0.000	0.005	0.052	0.05	ns	ns	ns
	P2	0.000	0.000	0.015		ns	ns	ns
Comparison (P)	1-2	ns	ns	ns				
E1 T2	P1	0.014	0.065	0.046		ns	ns	ns
	P2	0.001	0.062	0.053		ns	ns	ns
Comparison (P)	1-2	ns	ns	ns				
E1 T3	P1	0.026	0.056	0.093		ns	ns	ns
	P2	0.000	0.013	0.095		ns	ns	ns
Comparison (P)	1-2	ns	ns	ns				
E2 T1	P1	0.000	0.003	0.021		ns	ns	ns
	P2	0.001	0.000	0.042		ns	ns	ns
Comparison (P)	1-2	ns	ns	ns				
E2 T2	P1	0.124	0.227	0.041		ns	ns	ns
	P2	0.001	0.041	0.194		ns	ns	ns
Comparison (P)	1-2	ns	ns	ns				
E2 T3	P1	0.189	0.515	0.302		**	ns	*
	P2	0.001	0.041	0.211		ns	ns	ns
Comparison (P)	1-2	ns	**	ns				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-37. RELATIONSHIP AMONG MEANS FOR SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY POSITION OF FAILURE (P) BY LEG (L) FOR TUG CONTRIBUTION (CONT)

		Comparison (T)		
		L1	L2	L3
E1 P1	1-2	ns	ns	ns
	1-3	ns	ns	ns
	2-3	ns	ns	ns
E1 P2	1-2	ns	ns	ns
	1-3	ns	ns	ns
	2-3	ns	ns	ns
E2 P1	1-2	ns	ns	ns
	1-3	ns	**	*
	2-3	ns	**	**
E2 P2	1-2	ns	ns	ns
	1-3	ns	ns	ns
	2-3	ns	ns	ns

		Comparison (E)		
		L1	L2	L3
P1	T1	ns	ns	ns
	T2	ns	ns	ns
	T3	ns	**	*
P2	T1	ns	ns	ns
	T2	ns	ns	ns
	T3	ns	ns	ns

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE B-37. RELATIONSHIP AMONG MEANS FOR SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY POSITION OF FAILURE (P) BY LEG (L) FOR TUG CONTRIBUTION (CONT)

		Comparison (C)		
		L1	L2	L3
E1 T1	P1	ns	ns	ns
	P2	ns	ns	ns
E1 T2	P1	ns	ns	ns
	P2	ns	ns	ns
E1 T3	P1	ns	ns	ns
	P2	ns	ns	ns
E2 T1	P1	ns	ns	ns
	P2	ns	ns	ns
E2 T2	P1	ns	*	ns
	P2	ns	ns	*
E2 T3	P1	ns	**	**
	P2	ns	ns	*

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE B-38. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY LEG (L) FOR MEAN SPEED

	Time Course of Failure (T)	Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
C1 E1	T1	9.49	7.21	4.54	0.05	**	**	**
	T2	9.11	6.45	4.26		**	**	**
	T3	9.40	6.86	4.86		**	**	**
Comparison (T)	1-2	ns	**	ns				
	1-3	ns	ns	ns				
	2-3	ns	ns	ns				
C1 E2	T1	9.47	7.05	4.61		**	**	**
	T2	9.40	5.67	3.52		**	**	**
	T3	9.18	3.88	0.625		**	**	**
Comparison (T)	1-2	ns	**	**				
	1-3	ns	**	**				
	2-3	ns	**	**				
C2 E1	T1	9.61	7.43	4.56		**	**	**
	T2	9.41	6.75	3.95		**	**	**
	T3	9.45	6.68	3.88		**	**	**
Comparison (T)	1-2	ns	**	*				
	1-3	ns	**	*				
	2-3	ns	ns	ns				
C2 E2	T1	9.56	7.41	4.47		**	**	**
	T2	9.46	6.54	4.11		**	**	**
	T3	9.19	5.70	3.73		**	**	**
Comparison (T)	1-2	ns	**	ns				
	1-3	ns	**	**				
	2-3	ns	**	ns				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-38. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY LEG (L) FOR MEAN SPEED (CONT)

		Comparison (E)		
		L1	L2	L3
C1	T1	ns	ns	ns
	T2	ns	**	**
	T3	ns	**	**
C2	T1	ns	ns	ns
	T2	ns	ns	ns
	T3	ns	**	ns

		Comparison (C)		
		L1	L2	L3
E1	T1	ns	ns	ns
	T2	ns	ns	ns
	T3	ns	ns	**
E2	T1	ns	ns	ns
	T2	ns	**	*
	T3	ns	**	**

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE B-39. RELATIONSHIP AMONG MEANS FOR SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY POSITION OF FAILURE (P) BY LEG (L) FOR MEAN SPEED

	Position of Failure (P)	Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
E1 T1	P1	9.58	7.38	4.39	0.01	**	**	**
	P2	9.52	7.25	4.71		**	**	**
Comparison (P)	1-2	ns	ns	ns				
E1 T2	P1	9.20	6.37	4.36		**	**	**
	P2	9.32	6.83	4.85		**	**	**
Comparison (P)	1-2	ns	*	*				
E1 T3	P1	9.33	6.47	4.22		**	**	**
	P2	9.52	7.08	4.52		**	**	**
Comparison (P)	1-2	ns	**	ns				
E2 T1	P1	9.48	7.19	4.40		**	**	**
	P2	9.54	7.26	4.67		**	**	**
Comparison (P)	1-2	ns	ns	ns				
E2 T2	P1	9.20	5.37	3.98		**	**	**
	P2	9.65	6.83	3.65		**	**	**
Comparison (P)	1-2	*	**	ns				
E2 T3	P1	8.94	3.10	1.49		**	**	**
	P2	9.44	6.48	2.87		**	**	**
Comparison (P)	1-2	*	**	**				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-39. RELATIONSHIP AMONG MEANS FOR SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY POSITION OF FAILURE (P) BY LEG (L) FOR MEAN SPEED (CONT)

		Comparison (T)		
		L1	L2	L3
E1 P1	1-2	ns	**	ns
	1-3	ns	**	ns
	2-3	ns	ns	ns
E1 P2	1-2	ns	ns	ns
	1-3	ns	ns	ns
	2-3	ns	ns	ns
E2 P1	1-2	ns	**	*
	1-3	*	**	**
	2-3	ns	**	**
E2 P2	1-2	ns	*	**
	1-3	ns	**	**
	2-3	ns	ns	**

		Comparison (E)		
		L1	L2	L3
P1	T1	ns	ns	ns
	T2	ns	**	ns
	T3	ns	**	**
P2	T1	ns	ns	ns
	T2	ns	ns	ns
	T3	ns	**	**

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE B-40. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY SYSTEM EFFECTED (E) BY POSITION OF FAILURE (P) BY LEG (L) FOR MEAN SPEED

	Position of Failure (P)	Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
C1 E1	P1	9.27	6.71	4.45	0.001	**	**	**
	P2	9.40	6.98	4.66		**	**	**
Comparison (P)	1-2	ns	*	ns				
C1 E2	P1	9.16	4.68	2.91		**	**	**
	P2	9.54	6.38	2.92		**	**	**
Comparison (P)	1-2	*	**	ns				
C2 E1	P1	9.47	6.77	4.19		**	**	**
	P2	9.51	7.13	4.07		**	**	**
Comparison (P)	1-2	ns	*	ns				
C2 E2	P1	9.26	5.76	3.66		**	**	**
	P2	9.55	7.33	4.54		**	**	**
Comparison (P)	1-2	*	**	**				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-40. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY SYSTEM EFFECTED (E) BY POSITION OF FAILURE (P) BY LEG (L) FOR MEAN SPEED (CONT)

		Comparison (E)		
		L1	L2	L3
C1	P1	ns	**	**
	P2	ns	**	**
C2	P1	ns	**	**
	P2	ns	ns	**

		Comparison (C)		
		L1	L2	L3
E1	P1	ns	ns	ns
	P2	ns	ns	**
E2	P1	ns	**	**
	P2	ns	**	**

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE B-41. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY POSITION OF FAILURE (P) BY LEG (L) FOR MEAN TUG FORCE, $\bar{X}_T$

Tug Mode (C)		Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
C1	P1	0.000	0.000	0.000	0.001	ns	ns	ns
	P2	0.000	0.000	0.000		ns	ns	ns
	1-2	ns	ns	ns				
C2	P1	0.041	0.038	0.150		ns	**	**
	P2	0.002	0.027	0.194		*	**	**
	1-2	**	ns	**				
Comparison (C)	P1	**	**	**				
	P2	ns	**	**				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-42. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY LEG (L) FOR MEAN TUG FORCE, $\bar{X}_T$

	Time Course of Failure (T)	Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
C1 E1	T1	0.000	0.000	0.000	0.001	ns	ns	ns
	T2	0.000	0.000	0.000		ns	ns	ns
	T3	0.000	0.000	0.000		ns	ns	ns
Comparison (T)	1-2	ns	ns	ns				
	1-3	ns	ns	ns				
	2-3	ns	ns	ns				
C1 E2	T1	0.000	0.000	0.000		ns	ns	ns
	T2	0.000	0.000	0.000		ns	ns	ns
	T3	0.000	0.000	0.000		ns	ns	ns
Comparison (T)	1-2	ns	ns	ns				
	1-3	ns	ns	ns				
	2-3	ns	ns	ns				
C2 E1	T1	0.000	0.000	0.118		ns	**	**
	T2	0.032	0.055	0.174		ns	**	**
	T3	0.035	0.061	0.348		ns	**	**
Comparison (T)	1-2	ns	*	*				
	1-3	ns	**	**				
	2-3	ns	ns	**				
C2 E2	T1	0.001	0.007	0.150		ns	**	**
	T2	0.034	0.009	0.130		ns	**	**
	T3	0.027	0.062	0.110		ns	**	*
Comparison (T)	1-2	ns	ns	ns				
	1-3	ns	**	ns				
	2-3	ns	**	ns				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-42. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY LEG (L) FOR MEAN TUG FORCE, $\bar{X}_T$ (CONT)

		Comparison (E)		
		L1	L2	L3
C1	T1	ns	ns	ns
	T2	ns	ns	ns
	T3	ns	ns	ns
C2	T1	ns	ns	ns
	T2	ns	*	*
	T3	ns	ns	**

		Comparison (C)		
		L1	L2	L3
E1	T1	ns	ns	**
	T2	ns	**	**
	T3	ns	**	**
E2	T1	ns	ns	**
	T2	ns	ns	**
	T3	ns	**	**

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE B-43. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY TIME COURSE OF FAILURE (T) BY POSITION OF FAILURE (P) FOR MEAN TUG FORCE, $\bar{Y}_T$

Tug Mode (C)		Position of Failure P1	P2	Interaction p Value	Comparison (P)
C1	T1	0.000	0.000	0.05	ns
	T2	0.000	0.000		ns
	T3	0.000	0.000		ns
Comparison (T)	1-2	ns	ns		
	1-3	ns	ns		
	2-3	ns	ns		
C2	T1	0.030	0.024		ns
	T2	0.075	0.091		ns
	T3	0.176	0.106		**
Comparison (T)	1-2	*	**		
	1-3	**	**		
	2-3	**	**		
Comparison (C)	T1	ns	ns		
	T2	**	**		
	T3	**	**		

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE B-44. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY POSITION OF FAILURE (P) BY LEG (L) FOR MEAN TUG FORCE, $\bar{Y}_T$

Tug Mode (C)		Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
C1	P1	0.000	0.000	0.000	0.001	ns	ns	ns
	P2	0.000	0.000	0.000		ns	ns	ns
Comparison (P)	1-2	ns	ns	ns				
C2	P1	0.038	0.107	0.136		**	**	**
	P2	0.001	0.036	0.183		**	**	**
Comparison (P)	1-2	**	**	**				
Comparison (C)	P1	**	**	**				
	P2	ns	**	**				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-45. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY LEG (L) FOR MEAN TUG FORCE, $\bar{Y}_T$

	Time Course of Failure (T)	Leg (L) L1	L2	L3	Interaction p Value	Comparison (L) 1-2	1-3	2-3
C1 E1	T1	0.000	0.000	0.000	0.05	ns	ns	ns
	T2	0.000	0.000	0.000		ns	ns	ns
	T3	0.000	0.000	0.000		ns	ns	ns
Comparison (T)	1-2	ns	ns	ns				
	1-3	ns	ns	ns				
	2-3	ns	ns	ns				
C1 E2	T1	0.000	0.000	0.000		ns	ns	ns
	T2	0.000	0.000	0.000		ns	ns	ns
	T3	0.000	0.000	0.000		ns	ns	ns
Comparison (T)	1-2	ns	ns	ns				
	1-3	ns	ns	ns				
	2-3	ns	ns	ns				
C2 E1	T1	0.000	0.010	0.091		ns	**	**
	T2	0.008	0.076	0.127		**	**	*
	T3	0.013	0.038	0.175		ns	**	**
Comparison (T)	1-2	ns	**	ns				
	1-3	ns	ns	**				
	2-3	ns	ns	*				
C2 E2	T1	0.001	0.000	0.058		ns	*	**
	T2	0.033	0.083	0.169		*	**	**
	T3	0.063	0.221	0.336		**	**	**
Comparison (T)	1-2	ns	**	**				
	1-3	**	**	**				
	2-3	ns	**	**				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE B-45. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY SYSTEM EFFECTED (E) BY TIME COURSE OF FAILURE (T) BY LEG (L) FOR MEAN TUG FORCE, $\bar{Y}_T$ (CONT)

		Comparison (E)		
		L1	**L2**	**L3**
C1	T1	ns	ns	ns
	T2	ns	ns	ns
	T3	ns	ns	ns
C2	T1	ns	ns	ns
	T2	ns	ns	*
	T3	*	**	**

		Comparison (C)		
		L1	**L2**	**L3**
E1	T1	ns	ns	**
	T2	ns	**	**
	T3	ns	ns	**
E2	T1	ns	ns	**
	T2	ns	**	**
	T3	*	**	**

** $p < 0.01$
* $p < 0.05$
ns = not significant

APPENDIX C

TUG ASSISTANCE FOLLOWING FAILURE

In the derivation of the "inherent risk" factor, α, (Section 2-11) three recovery times were considered and in the estimation of α the effect of the tugs on the ship's trajectory after failure was neglected. The following simple analyses were performed to assess the magnitude of this assumption.

Suppose a ship is travelling due North in a narrow waterway with a speed u_o but with no yaw rate, side drift, etc. and in the absence of wind and current. At this point a complete failure takes place and tugs in attendance are called upon to exert control and prevent subsequent grounding. If the tug assistance were not considered and the ship continued at a constant speed thereafter (assuming hull drag to be negligible) it would advance a distance S in a time t_o where $S = u_o t_o$. This was the underlying assumption in the risk calculation.

Now, if the tugs can provide assistance instantaneously the subsequent ship's track (advance and transfer) can be estimated.

It is assumed that the tugs can be deployed in the following configurations, Figure C-1;

a) Both tugs are deployed to pull at the stern to produce maximum deceleration. Again, both are operating at full power and producing maximum forces.

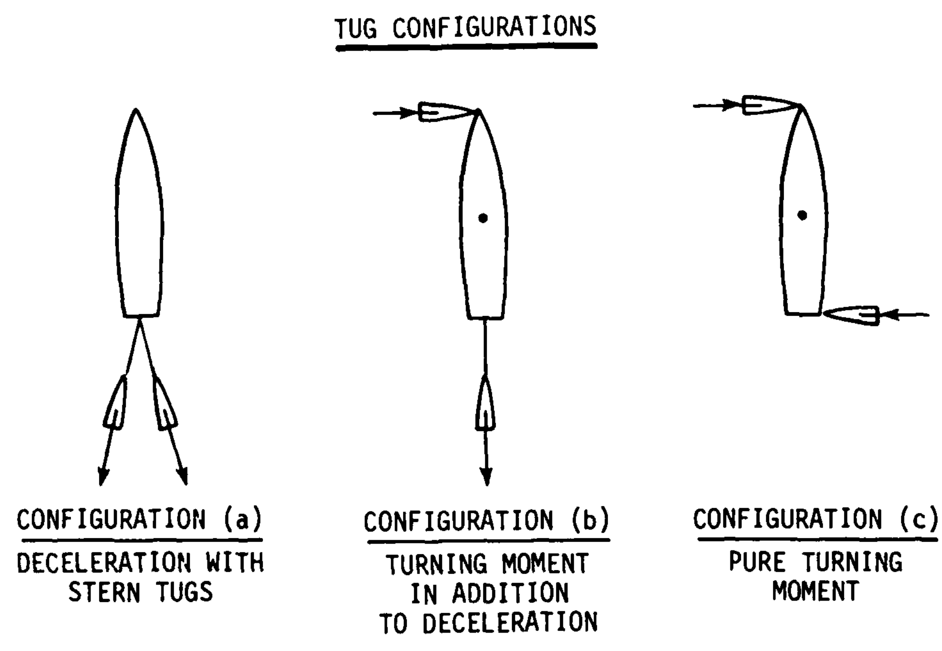

Figure C-1. Tug Configurations for Control Following Complete Failure

b) A tug at the stem exerting a yawing moment on the ship, while the second tug, pulling at the stern, produces a deceleration. Both tugs are working at full power and therefore giving their maximum forces.

c) Tugs pushing on the port bow and the starboard quarter at full power to produce a pure turning moment on the ship.

The solution in case (a) and case (c) require the application of an off-line ship-tug dynamics program that has been developed at CAORF, whereas case (b) can be solved readily. In this case the distance advanced (S) in time t_o is simply

$$S = u_o t_o - 1/2 \left(\frac{F}{m_{eff}}\right) t_o^2$$

where (F/m_{eff}) is the constant deceleration produced by the tug force F, and m_{eff} is the effective mass of the ship. This effective mass depends on the relative values of water depth and ship draft. A value of 1.10 is assumed here. The force F exerted by the two tugs is calculated from the total available horsepower (P) and a maximum bollard pull of 27 pounds per horsepower, i.e., F = 27 P.

The following calculations were performed for the 250,000 DWT tanker (m_{eff} = 19.25 x 10^6 slugs) travelling at 4.5 knots when failure occurs. The total tug horspower available is 8000 BHP.

Constant Speed Case

Without tug assistance the advance is simply S = $u_o t_o$ = 7.6 t_o or 1140, 2280 and 4560 feet for the same three times.

Configuration (a)

8000 BHP produces a maximum pull of 216,000 lb. The constant deceleration produced by this force on the 19.25 x 10^6 slug mass = 0.01122 feet/sec^2. The advances calculated for the three time periods selected (t_o = 2-1/2, 5 and 10 minutes) were 1014, 1776 and 2544 feet respectively. After 11.3 minutes the ship will be completely stopped and its advance at that time will be 2544 feet.

Configuration (b)

The ship-tug dynamics program was exercised to derive the advance and transfer for the 250,000 DWT tanker when two tugs were in attendance with a total of 8000 BHP available. The results indicated that there was again a constant deceleration along the curved track (0.00676 ft/sec^2 -- about 20% higher than would be produced by a stern tug alone, due to the hydrodynamic drag produced in turning). The results of this analysis are presented along with the results of the other analyses in Table C-1.

Configuration (c)

The ship tugs dynamics program was also used for this analysis. The results indicated a speed decrease in the curved track from 4.5 knots to 2.1 knots after 15 minutes, an approximately constant deceleration of 0.0045 ft/sec^2 about two-thirds of the value for configuration (b).

The resulting advances and transfers after 2-1/2, 5 and 10 minutes respectively are presented in Table C-1.

TABLE C-1. ADVANCE AND TRANSFER FOLLOWING FAILURE

250,000 DWT tanker, initial speed 4.5 knots with 8000 total tug power available.							
		Configuration (a)		Configuration (b)		Configuration (c)	
Time	Constant Speed	Advance	Transfer	Advance	Transfer	Advance	Transfer
2.5	1140	1014	--	1052	0	970	50
5.0	2280	1776	--	1952	200	2000	350
10.0	4560	2544	--	3245	900	3160	1500

An examination of the data in Table C-1 shows clearly that the tug influence on the ship's advance following a failure is negligible during the first few minutes and small even during the first five minutes. It is not until a period of up to ten minutes has elapsed that an appreciable difference in advances calculated under the different conditions is apparent. In addition, when one considers that, in practice, finite time lags actually occur before tugs become operative it appears reasonable to neglect the tug influence following the failure for times up to ten minutes as has been done here in calculating the risk factor α.

As pointed out previously the use of the tugs prior to the failure effects the ship's state variables at the time of failure, and in this way effects the subsequent α calculation.

APPENDIX D

SIMPLE INHERENT RISK CALCULATION

The geometry of the turn is shown in Figure D-1. The radius (R) of the transition arc is 5100 feet, and the half channel width of the legs on either side of turn is 400 feet. The ship is assumed to be perfectly on track and at some point, Q, defined by the angular coordinate θ, a complete failure takes place. The ship continues to move along the tangent to the arc QP with constant speed (U) and intersects the outer channel boundary at point P, where distance travelled, $S_0 = QP$. The lateral velocity of the stem or the stern is small

$$\left|\frac{v}{u}\right| = \frac{L}{2R} = \frac{1}{10}$$

and can be safely neglected in this calculation. Simple geometrical considerations show that the distance can be represented by

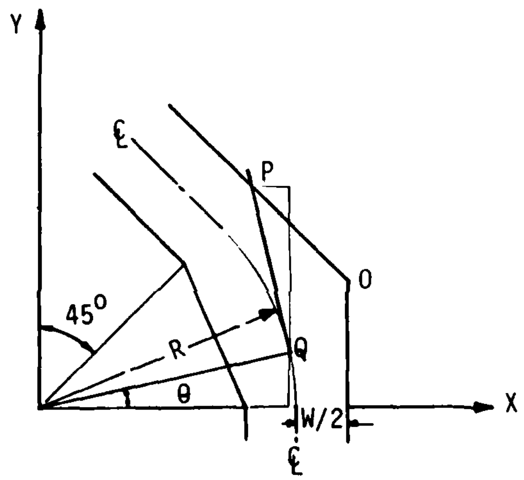

Figure D-1. Geometry For Risk Calculation

$$S_0 (\cos\theta - \sin\theta) = -R(\sin\theta + \cos\theta) + (R + \frac{W}{2})(1 + \tan 22\text{-}1/2^{\circ})$$

or

$$S_0 (\cos\theta - \sin\theta) = -5100(\sin\theta + \cos\theta) + 7778$$

The distance moved by the CG of the ship before its stem crosses the channel boundary is $S_G = (S_0 - L/2)$. The following Table of values of distance to grounding against ship position (θ) at failure was derived.

TABLE D-1. SHIP SPEED FOR NO GROUNDINGS

θ	S (feet)	Max. Ship Speed For No Grounding (kts)
0	2138	4.22
10	1762	3.48
15	1624	3.20
20	1534	3.03
22-1/2	1516	2.99
30	1676	3.31
35	2211	4.36
40	4275	8.43
45	infinite	--

On the assumption that recovery can take place in a period of five minutes (as discussed in Appendix C) a maximum value of ship speed at each position on the transition arc was also obtained, above which the local inherent risk of grounding was unity. The most critical point corresponds to halfway around the arc (θ = 22-1/2°)

and indicates that a speed of three knots or less would be necessary for no inherent risk, that is $\alpha_2 = 0$ for leg 2. If the speed were four knots or over this inherent risk would be high throughout the turn and α_2 would closely approach unity. This shows that the small margin of one knot could be critical should a complete failure take place.

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